Climate Applications in Forest Renewal and Forest Production

Edited by
D.C. MacIver, R.B. Street,
and A.N. Auclair

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Natural
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Ontario

Climate Applications in Forest Renewal and Forest Production

Proceedings of Forest Climate '86
November 17-20, 1986
Geneva Park, Orillia, Ontario

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Preface

This symposium/workshop provided an opportunity for practicing foresters to dialogue with applied climatologists on several key issues in forest renewal and forest production. Forest Climate '86 stressed the importance of climatic impacts and applications in operational forest management problems. In addition, uncertainties, new development directions, and climatic techniques and products were demonstrated for a variety of forest climatology applications.

Forest Climate '86 was the first reunion since 1968 in which foresters and climatologists have gathered in a national scientific/technical forum within Canada to discuss advances and problems related to forest climatology. As evident from the presentations at the symposium/workshop and the papers contained within these proceedings, this meeting was long overdue. We hope that the next meeting of this type will not have to wait another 20 years.

A meeting of this type does not just happen but requires the involvement of many individuals and organizations. We would like to acknowledge and thank all those who were involved, for without their cooperation and participation Forest Climate '86 would not have been a success. Specifically we would like to thank:

- Cooperating agencies who supplied funds and made available their resources including:
    - Atmospheric Environment Service, Environment Canada
    - Canadian Forestry Service, Agriculture Canada
    - Canadian Meteorological and Oceanographic Society
    - Ontario Ministry of Natural Resources
- Moderators who kept the sessions focused and on-schedule:
    - Dr. L. Zsuffa, University of Toronto, Toronto, Ontario
    - Mr. D. Drysdale, Ontario Ministry of Natural Resources, Maple, Ontario
    - Mr. J. Cayford, Canadian Forestry Service, Sault Ste. Marie, Ontario
    - Mr. B. Bourchier, Canadian Institute of Forestry, Ottawa, Ontario
    - Mr. P. Aber, Atmospheric Environment Service, Toronto, Ontario
    - Mr. J. Walker, Canadian Forestry Service, Chalk River, Ontario
    - Dr. D. Burger, Ontario Ministry of Natural Resources, Maple, Ontario
    - Dr. J. Powell, Canadian Forestry Service, Edmonton, Alberta
    - Mr. M. Flannigan, Canadian Forestry Service, Chalk River, Ontario
- Geneva Park Conference Centre staff who provided a comfortable and productive environment for the symposium/workshop
- CFS-AES CCP Working Group on Forest Climatology and Meteorology whose members initiated the concept of Forest Climate '86 and lended their support at various stages
- The conference organizing committee of Don C. MacIver, Roger B. Street, and Allan N. Auclair
- The editorial committee of Don C. MacIver, Roger B. Street, Paul Addison, Steve Masarovich, and Allan N. Auclair
- Steve Masarovich for his organization of the poster session both in terms of the conference logistics and the organization of the poster presentations in these proceedings
- M. Lemaire and P. Sajecki who provided support during the conference
- U. Ellis, P. Burke, and W. Johnson of the Publication and Micrographic Section of the Canadian Climate Centre of the Atmospheric Environment Service for their assistance in the preparation of the text of this proceedings and the preprint abstract volume
- J. Tomlinson and P. Irving of Scientific and Technical Publications, Canadian Forestry Service, who greatly facilitated the preparation of this volume for publication and the production of the workshop/symposium brochure
- All those who participated in Forest Climate '86.

Don C. MacIver and Roger B. Street

Préface

Ce symposium/atelier de travail a donné l'occasion à des praticiens en foresterie de dialoguer avec des spécialistes de la climatologie appliquée sur plusieurs questions clés relatives au renouvellement de la forêt et à la production forestière. «Climatologie forestière 1986» a souligné l'importance des effets climatiques et de leurs applications dans la gestion opérationnelle des forêts. De plus, on a fait état à ce symposium des incertitudes et des nouvelles orientations en matière de développement et on a fait connaître des techniques et des produits relatifs au climat en fonction de diverses applications de la climatologie forestière.

«Climatologie forestière 1986» est la première réunion depuis 1968, qui a rassemblé des forestiers et des climatologues dans un forum national, scientifique et technique, pour discuter des problèmes et progrès en matière de climatologie forestière. Comme le font ressortir les communications présentées à ce symposium/atelier de travail et les articles contenus dans ces comptes rendus, cette réunion était attendue depuis longtemps. Nous espérons que la prochaine rencontre de ce type ne se fera pas attendre pendant encore 20 ans.

Une telle réunion ne se fait pas toute seule; elle exige un engagement de la part de beaucoup de personnes et d'organisations. Nous voudrions remercier tous ceux qui y ont consacré du temps et des énergies car, sans leur collaboration et leur participation, «Climatologie forestière 1986» n'aurait pas été une réussite. En particulier, nous aimerions remercier:

- Les organismes coopérants qui ont fourni des fonds et mis à notre disposition leurs ressources, notamment:
  - Le Service de l'environnement atmosphérique, Environnement Canada,
  - Le Service canadien des forêts, Agriculture Canada,
  - La Société canadienne de météorologie et d'océanographie,
  - Le ministère ontarien des Ressources naturelles.
- Le personnel du Geneva Park Conference Centre qui a tout fait pour créer un environnement confortable et propice au travail.
- Le Groupe de travail SCF-SEA sur la climatologie forestière, dont les membres ont lancé l'idée de «Climatologie forestière 1986» et ont offert leur appui à différentes étapes.
- Le Comité d'organisation de la conférence: Don C. MacIver, Roger B. Street, P. Addison, S. Masarovich et Allan N. Auclair.
- Steve Masarovich qui a organisé la séance des affiches (posters) et qui s'est occupé de la logistique de la conférence et de l'organisation des présentations des affiches dans ce compte rendu des délibérations.
- M. Lemaire et P. Sajicki qui ont offert leur aide au cours de la conférence.
- U. Ellis, P. Burke et W. Johnson, de la Section de la publication et de la micrographie, Centre climatologique canadien, Service de l'environnement atmosphérique, qui ont aidé à préparer le texte de ce compte rendu ainsi que le volume de résumés en préimpression.
- J. Tomlinson et P. Irving, de la Division des publications scientifiques et techniques, Service canadien des forêts, qui ont grandement facilité la préparation de ce volume pour la publication et la production de la brochure sur le symposium/atelier de travail.
- Tous ceux qui ont participé à «Climatologie forestière 1986».

Don C. MacIver et Roger B. Street

Abstract

Forest Climate '86, the multiagency-sponsored symposium/workshop on climate applications in forest renewal and forest production proved highly successful in evaluating today's level of forest-climate knowledge. The symposium/workshop forum provided an opportunity for dialogue among the climatologists, forest managers, and researchers regarding uncertainties, new development directions, and climatic techniques and products related to a variety of forestry problems and activities.

The presentations during the sessions (both oral and poster presentations) clearly demonstrated that some progress had been made in terms of the integration of forest-climate concepts into operational forestry. Expertise exists within several public and private agencies in the general areas of forest renewal, forest production, and high-tech applications in operational forest-climate management. During Forest Climate '86, successful applications of forest-climate concepts (both real and potential) were highlighted, covering the full spectrum of forestry operations from the identification of seed and productivity zones to harvesting and utilization. However, significant gaps and/or weaknesses were also demonstrated and must be addressed.

In general, Forest Climate '86 demonstrated that forest-climate knowledge and technology have made significant progress towards operationally assisting the forest manager in both forest renewal and production within a positive economic framework. The transfer of knowledge/technology/products has in most cases not been effective and a greater emphasis on training workshops and interagency teams is strongly advocated. The following set of comments and recommendations addresses the successes and weaknesses demonstrated during Forest Climate '86 and provides a framework for future forest climatology activities.

In total 31 recommendations have been proposed directly related to the four major sessions at the Forest Climate '86 symposium, namely Climatic Applications in Seed and Stock Production, Climatic Applications in Forest Regeneration, Climatic Applications in Forest Growth and Development, and Climatic Applications in Forestry Utilization and Economics (rationales and recommendations are provided in each session chapter with a summary provided in the appendix).

From this list the following seven recommendations are proposed for immediate action:

1) Upgrading, standardization, and quality control of the climate-observing procedures, network designs, climatic hardware (automatic dataloggers), and computerized software at all nursery and seed orchard locations.

2) Process studies and models to analyze and integrate climate and weather into day-to-day forestry operations. (In many cases, the climate knowledge and technology is currently available.)

3) Atmospheric–forestry programs focusing directly on the growth layer–climate–wood density interactions within the context of related stresses in the new and old forest.

4) Assessment and modeling of the physiological sensitivity and response of forest stands to climate, its variability, and its changing physical and chemical structures.

5) Climate stresses (including airborne pollution) be identified, evaluated, and documented and this information recorded annually as volume depletions (or accelerations) in forest management planning procedures and allowable cut models.

6) Sponsorship of interagency teams to increase the delivery, effectiveness, and implementation of current climatic knowledge and technology into forest renewal and production practices.

7) The need for updating and improving fire weather station networks (i.e., siting and instrumentation) be examined and the possibility of multipurpose (i.e., fire and silviculture) weather stations be explored. This process can be relatively simple and inexpensive considering the increasing availability of reasonably priced automated dataloggers.

Résumé

«Climatologie forestière 1986», le symposium/atelier de travail parrainé par divers organismes et portant sur les applications des données climatiques au renouvellement de la forêt et à la production forestière, a très bien réussi à évaluer le niveau actuel de nos connaissances sur le climat et la forêt. Ce forum a permis d'établir un dialogue entre climatologues, aménagistes forestiers et chercheurs sur les incertitudes, les nouvelles orientations en matière de développement, les technologies et les produits reliés au climat en fonction de divers problèmes et activités forestières.

Les exposés présentés au cours des séances (à la fois oralement et sous forme d'affiches) ont montré clairement qu'on avait fait des progrès en ce qui concerne l'intégration de la notion de climat forestier à l'exploitation forestière.

Il y a des compétences à l'intérieur de plusieurs organismes publics et privés dans les domaines généraux du renouvellement des forêts, de la production forestière et des applications de la technologie de pointe dans la gestion opérationnelle du climat et de la forêt. Au cours du symposium, on a mis en lumière les applications réussies des notions de climat forestier (à la fois réelles et potentielles) en passant en revue toute la gamme des opérations forestières depuis l'identification des graines et les zones de productivité jusqu'à la récolte et à l'utilisation. Cependant, on a aussi mis en évidence des lacunes ou faiblesses importantes auxquelles il faut remédier.

En général, le symposium a montré que nos connaissances et notre technologie en matière de climat forestier ont beaucoup contribué à aider l'aménagiste forestier à s'acquitter de ses tâches dans les domaines du renouvellement des forêts et de la production forestière tout en respectant les objectifs économiques fixés. Dans la plupart des cas, le transfert des connaissances, de la technologie et des produits n'a pas été efficace et les participants ont fortement souligné l'importance des ateliers de formation et des équipes interministérielles. La série de commentaires et de recommandations qui suivent tiennent compte des réussites et des lacunes qu'a révélées le symposium et ils fournissent un cadre pour les activités futures en climatologie forestière.

On a proposé, au total, 31 recommandations directement reliées aux sujets débattus lors des quatre principales séances du symposium «Climatologie forestière 1986», à savoir les applications des données climatiques à la production de graines et de plantes-mères, au repeuplement de la forêt, à la croissance et au développement des forêts et enfin à l'utilisation des produits forestiers et à l'économie forestière (on trouvera les analyses et les recommandations dans le chapitre consacré à chaque séance ainsi qu'un résumé dans l'annexe).

Voici, tirées de cette liste, sept recommandations qu'on propose de mettre en application immédiatement:

1) Amélioration, normalisation et contrôle de la qualité en ce qui concerne les procédures d'observation du climat, la conception des réseaux, le matériel nécessaire pour les données climatiques (enregistreurs de données automatiques) et les logiciels dans toutes les pépinières et les vergers producteurs de graines.

2) Études et modèles de procédés pour analyser et intégrer les données climatiques et les conditions atmosphériques dans les opérations forestières courantes. (Dans beaucoup de cas, on dispose actuellement de connaissances et de technologies en ce qui concerne le climat.)

3) Programmes portant sur les forêts et les conditions atmosphériques et concentrés directement sur les interactions entre la croissance, la couche d'accroissement, le climat et la densité du bois dans le contexte des contraintes qui y sont associées dans les forêts jeunes ou vieilles.

4) Évaluation et modélisation de la sensibilité physiologique et réponse des peuplements des forêts aux conditions du climat, à sa variabilité et à l'évolution de ses structures physiques et chimiques.

5) Identification, évaluation et étude documentée des contraintes imposées par le climat (notamment la pollution atmosphérique) et enregistrement annuel de ces informations à titre d'épuisement de volume (ou accélérations) dans la planification de l'aménagement des forêts et les modèles de coupe admissible.

6) Parrainage d'équipes interministérielles pour accélérer la diffusion, l'efficacité et l'application des connaissances et technologies actuelles en matière de climat au renouvellement des forêts et aux méthodes de production.

7) Examiner s'il faut moderniser et améliorer les réseaux de stations de forêt-météo (lieu d'implantation et instruments) et explorer la possibilité d'installer des stations météorologiques à objectifs multiples (feu et sylviculture). Ce processus peut être relativement simple et peu coûteux étant donné qu'on trouve de plus en plus des enregistreurs de données automatiques à des prix raisonnables.

Welcoming Remarks

H.L. FERGUSON
Assistant Deputy Minister, Atmospheric Environment Service, Environment Canada
Presented by
J.A.W. MCCULLOCH
Director General, Canadian Climate Centre, Atmospheric Environment Service

I would like to convey the best wishes of Assistant Deputy Minister Mr. H.L. Ferguson. He regrets that he cannot be with you today.

The opportunity to represent Mr. Ferguson and to welcome you to this workshop is a real pleasure for me. This is my first official external activity since assuming the position of director general of the Canadian Climate Centre two weeks ago. It is fitting that my first external contact be in the area of forestry since weather and climate are closely related to all phases of forestry activities. This close relationship is particularly evident after reviewing the program of this workshop. For daily operations, the significant role of the actual and forecast weather is self-evident to most individuals involved. However, the presentations at this workshop will further demonstrate the importance of climate (i.e., historical averages and their variations dealing with chemical alteration of the atmosphere and the chemical pollutants and the transport of toxics and other pollutants through atmospheric pathways). The significance of these processes to the forest industry is being demonstrated by current research initiatives. However, the possible impacts of radiatively active gases (e.g., CO_2 and methane) on our climate and thus forestry are also significant. The work presented at this workshop over the next few days will have only transitory interest if the potential impacts of climatic variability and climate change are not taken into consideration.

It is clear that there is a significant interdisciplinary aspect to the work represented at this workshop; that is why this meeting is so important. I became aware of this a number of years ago when my son was doing an undergraduate thesis under Professor Don MacIver at York University. The total project covered variability in tree growth over short distances that could be due to microclimate, soils, the stock involved, or a combination of the above. One weekend on the way back from the cottage I helped him install the soil thermometers and the soil moisture sensors. Professor MacIver assures me that the microclimate was adequately described. Unfortunately, the total project did not achieve its goals because the three aspects that were potential contributors were limited in their opportunities to fully integrate their studies. I get the impression from reading the abstracts provided for this workshop that for the work to be presented to you, the disciplines did get together successfully.

I would like to close my remarks with a plea. During the meeting, from time to time, please direct your thoughts to the question of how a different temperature or precipitation regime would have made a difference to the results being reported. What would be the impact on the science and the industry of significant variations in climate or even a more permanent change? What kinds of joint programs between climatologists, foresters, and others could lead to credible guidance for decision-makers on how to mitigate the social and economic impacts of climate change? I know that your first inclination will be to suggest that until the climatologists can provide reliable guidance on the extent of possible changes, there is little you could do. I would like to disagree. Given that the meteorologists and climatologists could only make statements about potential ranges of variation and change, much is possible. The kind of modeling demonstrated in the paper last evening as presented by Dr. Perttu provides a possible mechanism for doing so.

On behalf of the Atmospheric Environment Service, I hope that the interest and excitement of the paper presented last evening by Dr. Perttu carries on for the remainder of this workshop, and that you all leave here on Thursday intellectually and socially satisfied.

Allocution de bienvenue

H.L. Ferguson

Sous-ministre adjoint, Service de l'environnement atmosphérique, Environnement Canada

présentée par

J.A.W. McCulloch

Directeur général, Centre climatologique canadien, Service de l'environnement atmosphérique

Le sous-ministre adjoint, Monsieur H.L. Ferguson, me prie de vous transmettre ses meilleurs voeux. Il regrette de ne pouvoir se joindre à nous aujourd'hui.

L'occasion de représenter Monsieur Ferguson pour vous souhaiter la bienvenue à cet atelier est un grand plaisir pour moi. Il s'agit de ma première activité officielle extérieure depuis que j'ai assumé les fonctions de directeur général du Centre climatologique canadien, il y a deux semaines. Il est juste que mon premier contact extérieur soit dans le secteur de l'exploitation forestière étant donné l'étroite relation des conditions météorologiques et du climat avec toutes les phases des activités forestières. Ce lien étroit est particulièrement mis en évidence par l'examen du programme de cet atelier. Dans les activités quotidiennes, le rôle important des conditions météorologiques actuelles et prévues est évident pour la plupart des travailleurs du secteur. Cependant, les communications présentées à cet atelier démontreront encore plus l'importance du climat (c'est-à-dire les moyennes historiques et leurs variations relativement à la modification chimique de l'atmosphère, aux polluants chimiques et au transport de substances toxiques et d'autres polluants par des voies atmosphériques). L'importance de ces phénomènes pour l'industrie forestière est démontrée par les initiatives actuelles en recherche. Toutefois, les impacts possibles des gaz radiatifs (par exemple le CO_2 et le méthane) sur notre climat et, en conséquence, sur l'exploitation forestière, sont également importants. Les travaux présentés à cet atelier au cours des prochains jours n'auront qu'un intérêt passager si l'on ne tient pas compte des impacts possibles de la variabilité et de l'évolution du climat.

Cet atelier revêt un intérêt particulier en raison de l'aspect interdisciplinaire des travaux qui y seront présentés. J'ai compris cette relation il y a un certain nombre d'années, lorsque mon fils rédigeait une thèse de premier cycle sous la direction du professeur Don MacIver à l'Université York. Le projet complet couvrait la variabilité de la croissance des arbres sur de faibles distances, attribuable au microclimat, aux sols, aux plants utilisés ou à une combinaison de ces facteurs. Sur le chemin du retour après une fin de semaine au chalet, je l'aidais à installer des géothermomètres ainsi que des détecteurs d'humidité dans le sol. Le professeur MacIver m'a assuré que le microclimat a été bien décrit. Malheureusement, les objectifs du projet complet n'ont pas été atteints parce que les possibilités d'intégration des études de trois aspects contributeurs potentiels étaient limitées. En lisant les résumés présentés à cet atelier, je crois que les disciplines des travaux qui vous seront exposés ont été fusionnées avec succès.

Je terminerai mes remarques en vous demandant une faveur. Vous serait-il possible de temps en temps, au cours de la réunion, de tenter d'évaluer l'effet d'un régime différent de températures ou de précipitations sur les résultats présentés? Quel serait l'impact d'importantes variations climatiques ou même d'un changement plus permanent sur la science et l'industrie forestière? Quels types de programmes entrepris conjointement par des climatologistes, des forestiers et d'autres spécialistes permettraient d'orienter plus sûrement les décideurs qui cherchent à atténuer les impacts sociaux et économiques du changement climatique? Je sais qu'instinctivement vous répondrez qu'il n'y a pas grand-chose à faire tant que les climatologistes ne pourront pas fournir une information fiable sur l'étendue des changements possibles. Or, je ne partage pas cette opinion. Il existe beaucoup de possibilités, même si les météorologistes et les climatologistes ne fournissent que des hypothèses sur les gammes possibles de variations et de changements. Le type de modélisation présenté dans l'exposé de Monsieur Perttu (Ph.D.), hier soir, offre un mécanisme possible pour atteindre cet objectif.

Au nom du Service de l'environnement atmosphérique, j'espère que l'intérêt et l'enthousiasme suscités par l'exposé de Monsieur Perttu persisteront pendant toute la durée de cet atelier et que jeudi vous partirez tous satisfaits tant sur le plan intellectuel que sur le plan social.

Welcoming Remarks

JEAN CLAUDE MERCIER
Associate Deputy Minister, Canadian Forestry Service
Presented by
J.M. CAYFORD
Regional Director General
Great Lakes Forestry Centre, Sault Ste. Marie, Ontario

Mr. Chairman, distinguished guests, ladies and gentlemen: On behalf of Mr. Mercier, it is a privilege for me to welcome you as participants in Forest Climate '86. We in the Canadian Forestry Service are proud of our programs and contributions to your working groups that have helped lead to this symposium.

To begin with, we have a long-standing involvement in research into climatic effects on the forest. For almost a quarter of a century we have studied climatic impacts on forestry. We recognized long ago that the processes at work in our climate play a major role in controlling the types of forests we have in Canada, as well as their susceptibility to diseases, insects, and fire. This has led to the need for research into the relationships between climate and damage-causing agents and for developing the means to include climate as a variable in the planning for silviculture, management, and harvesting.

In 1980, the CFS further demonstrated its commitment to the understanding of climate by initiating cooperatively with the Atmospheric Environment Service the forest climate working group. We have expanded our ongoing climatic studies and today I would just like to highlight a few of these projects for you.

We are researching the impact of climate on Canada's boreal forest biomass. The boreal forest is Canada's largest forest region; however, prevailing climate and the available nutrients impose restraints that result in low forest productivity. Therefore, to use the forest resource most effectively, we must know the climatic relationships to forest productivity.

In a closely related area we have designed the fire danger rating systems, which along with the national grid coding systems, are essential to the efficient operation of the fire weather forecasting system. Annually we lose about 13 000 square kilometres of productive forest land to some 9000 forest fires. Our annual firefighting costs are approximately $150 million. Increasingly, we have become aware that the ecological and economic implications of forest fire behavior should be considered an integral factor in our forest management.

Weather has an intimate relationship with aerial spraying for forest pests. We are currently studying the effects of weather on spray behavior so that we can improve the efficacy of forest pesticide applications as well as reduce their environmental impact. To date, this project has given us guidelines for the meteorological conditions under which spraying should be carried out. Because of the need to predict spray drift, research is focused on spray cloud behavior under different atmospheric conditions and various spray technologies.

Climatic change will become an increasingly important factor in forest management. We recognize that at the end of the life span of the trees we are now planting, they will probably be harvested in a climate and carbon dioxide atmosphere much different from what we now have.

The Canadian Forestry Service will need to be more intimately involved in predicting climate and, more specifically, examining how our planting, silviculture, management, and harvesting practices may have to be altered to respond to anticipated climatic changes.

This symposium is of particular value to those of us engaged in forestry policy-making as a guide to dealing with the situations imposed by change, including those of climate. Therefore, may I conclude by welcoming you to Forest Climate '86 and may I also wish you fruitful deliberations and discussions during this symposium.

Allocution de bienvenue

Jean Claude Mercier
Sous-ministre associée, Service canadien des forêts
présentée par
J.M. Cayford
Directeur général régional, Centre de foresterie des Grands Lacs, Sault Ste. Marie (Ontario)

Monsieur le président, distingués invités, mesdames et messieurs, au nom de Monsieur Mercier, j'ai l'honneur de vous souhaiter la bienvenue en qualité de participants à «Climatologie forestière 86». Le Service canadien des forêts est fier de ses programmes et de ses contributions à vos groupes de travail qui ont donné naissance à ce symposium.

En premier lieu, notre engagement dans le secteur de la recherche sur les effets climatiques en milieu forestier n'est pas récent. Depuis près d'un quart de siècle, nous étudions l'impact climatique sur l'exploitation forestière. Il y a fort longtemps, nous avons conclu que les phénomènes actifs de notre climat ont un effet déterminant sur les types de forêts qui croissent au Canada ainsi que sur leur vulnérabilité aux maladies, aux insectes et aux incendies. Il fallait donc étudier les relations entre le climat et les agents destructeurs et trouver le moyen d'inclure le climat comme variable dans la planification de la sylviculture, de la gestion et de la récolte.

En 1980, le SCF a démontré une fois de plus sa détermination à mieux comprendre le climat en créant conjointement avec le Service de l'environnement atmosphérique le groupe de travail sur la climatologie forestière. Nous avons élargi le champ de nos études climatologiques en cours et, aujourd'hui, j'aimerais vous présenter un aperçu de quelques-uns de ces projets.

Nous étudions l'impact du climat sur la biomasse forestière boréale du Canada. La forêt boréale constitue la plus grande région forestière au Canada. Cependant, le climat dominant et les éléments nutritifs accessibles imposent des contraintes qui sont à l'origine d'une faible productivité forestière. En conséquence, nous devons connaître les relations entre le climat et la productivité forestière pour utiliser les ressources des forêts de la façon la plus efficace.

Dans un secteur étroitement associé, nous avons conçu le système de cotation des risques d'incendie qui, avec le système national de classement par quadrillage, est essentiel à l'exploitation efficace du système de prévision des conditions météorologiques favorables aux incendies. Chaque année, quelque 9 000 incendies de forêt détruisent environ 13 000 km² de terres forestières productives. La lutte contre les incendies de forêt nous coûte environ 150 millions de dollars par an. De plus en plus, nous nous rendons compte que les conséquences écologiques et économiques du comportement des incendies de forêt sont des facteurs qui doivent être intégrés à notre gestion forestière.

Les conditions météorologiques constituent une composante majeure de la pulvérisation aérienne contre les ravageurs forestiers. Nous étudions actuellement les effets de ces conditions sur le comportement des bruines de façon à améliorer l'efficacité des applications de pesticide forestier et à réduire leur impact environnemental. Jusqu'à présent, ce projet nous a permis d'établir des lignes directrices quant aux conditions météorologiques dans lesquelles les pulvérisations sont effectuées. Étant donné la nécessité de prévoir la dérive du produit pulvérisé, la recherche est axée sur le comportement du nuage dans différentes conditions atmosphériques et pour diverses techniques de pulvérisation employées.

Le changement climatique est un facteur dont l'importance augmentera de façon croissante en gestion forestière. Nous savons que, lorsqu'il sera temps de récolter les arbres que nous plantons actuellement, le climat ainsi que la concentration atmosphérique de gaz carbonique seront probablement fort différents de ce qu'ils sont aujourd'hui.

Le Service canadien des forêts devra participer plus étroitement aux prévisions climatiques et, en particulier, examiner comment il faudra modifier nos méthodes de plantage, de sylviculture, de gestion et de récolte pour qu'elles soient adaptées aux changements climatiques anticipés.

Ce symposium offre un grand intérêt pour ceux d'entre nous qui participent à l'élaboration d'une politique forestière comme guide visant à résoudre les problèmes imposés par le changement, y compris l'évolution climatique. Je conclus donc en vous souhaitant la bienvenue à «Climatologie forestière 86», et puissiez-vous y connaître de fructueuses délibérations et discussions.

Welcoming Remarks

B. Burgar

Assistant Deputy Minister, Ministry of Natural Resources

On behalf of the Ontario Ministry of Natural Resources, let me extend a warm welcome to all speakers and participants, especially to our national and international visitors.

Forest climate workshops are not a regular event in Canada, and we are pleased to have Ontario selected as the host province in cooperation with the Canadian Forestry Service and the Atmospheric Environment Service, Environment Canada.

There is no question that climate directly affects wood production. The province of Ontario reflects a significant range of mean air temperatures for the May–September growing season from 20°C in the south to 10°C in our northern locations, and many locations report mean annual temperatures below freezing. Likewise, significant variability in total precipitation for the May–September growing season ranges from 340 to 480 mm. The photosynthetic capacity of the forest responds to these thermal and moisture interrelationships by displaying a range of forest species and production levels throughout the province.

Our ministry has been particularly active in forest climate research, development, and operational management. In many cases, strong cooperation with the Canadian Forestry Service; the Atmospheric Environment Service, Environment Canada; and other federal, provincial, university, and private sector cooperators has proved extremely rewarding. Let me take a few moments to expand on some highlights:

- A climatic-based irrigation model has been developed in cooperation with the Atmospheric Environment Service to support our genetic seed orchard programs in northwestern Ontario.
- Six of our provincial nurseries have been upgraded with CR-21 micrometeorological towers and computers to support ongoing nursery practices, and to develop an integrated irrigation scheduling model.
- Numerous regional growth and development studies are under way throughout Ontario, which include climate as an integral ingredient for operational forest management planning. In some cases, our ministry has developed new computerized TRIM technology to improve our understanding of growth and development.
- Our ministry is also involved in numerous climate-related studies for forecasting the production forest and the potential treatment options. For example, owing to the climatic complexities throughout Ontario, we are irrigating seed orchards in the northwest, whereas in other northern areas of the province we are investing money in draining timber land to increase its production.
- Losses or depletion of our timber resources are a major concern to any forest agency. Again, our ministry is a major cooperator with other agencies, especially in the areas of (1) fire: where meteorological fire forecasting has provided tremendous savings to our natural forest resource; (2) insects and diseases: where the definition of the climatic "window" for effective spraying is extremely important; (3) air pollution: where understandably the atmosphere again is a significant concern for long-term forest management. Within this context of growth, development, and losses, the forest must also adapt to long-term climatic change.

To the timber forester on the ground, forest management strategies for Ontario must be developed within these climatic complexities in the context of both the "old" producing forest and the "new" regenerated forest.

Our ability to biologically store future timber supplies "on the stump" depends on the prevailing climatic stresses throughout Ontario. The harsh northern climates create special challenges for the harvesting and transportation of timber to the mills. Yet it is within these climates that Ontario must remain strongly competitive in the international marketplace.

Integrated uses of our forest resource must also be addressed, and new initiatives explored. Timber production is but one of many benefits provided by Ontario's forest resource. Here, too, climate plays an important role for wildlife and fisheries management, and outdoor recreation.

The combined efforts of universities, government, and private industry are required to accomplish these goals. The solution will not come easily, and today's workshop is a first step in the right direction.

Again, welcome to Ontario, and may you be well "weathered" by the conclusion of this workshop.

Allocution de bienvenue

B. Burgar

Sous-ministre adjoint, Ministère des Richesses naturelles

Au nom du ministère des Richesses naturelles de l'Ontario, je souhaite la bienvenue à tous les conférenciers et participants, et particulièrement à nos visiteurs nationaux et internationaux.

Au Canada, les ateliers de climatologie forestière ne sont pas des activités organisées régulièrement, et nous sommes très heureux que l'Ontario ait été choisi comme province hôte en collaboration avec le Service canadien des forêts et le Service de l'environnement atmosphérique d'Environnement Canada.

Il n'y a aucun doute que le climat a un impact direct sur la production du bois. L'Ontario présente une gamme étendue de températures moyennes de l'air au cours de la saison de croissance végétale de mai à septembre, qui varient de 20 °C dans le Sud à 10 °C dans le Nord, de nombreux endroits signalant par ailleurs des températures annuelles moyennes sous le point de congélation. De même, on observe une variabilité importante dans les précipitations totales qui tombent de mai à septembre, soit de 340 à 480 mm. La capacité de photosynthèse de la forêt réagit à ces interrelations de température et d'humidité en déployant toute une gamme d'espèces forestières et de niveaux de production sur l'étendue du territoire de la province.

Notre ministère s'est montré particulièrement actif dans la recherche, le développement et la gestion opérationnelle de la composante du climat forestier. Dans de nombreux cas, une étroite coopération avec le Service canadien des forêts, le Service de l'environnement atmosphérique d'Environnement Canada ainsi qu'avec d'autres collaborateurs des gouvernements fédéral et provinciaux, du milieu universitaire et du secteur privé s'est révélée extrêmement fructueuse. Je prends ici quelques instants pour vous en donner un aperçu.

- On a mis au point, en collaboration avec le Service de l'environnement atmosphérique d'Environnement Canada, un modèle d'irrigation basé sur le climat pour appuyer nos programmes de vergers à graines de familles dans le nord-ouest de l'Ontario.
- Six de nos pépinières provinciales ont été équipées d'ordinateurs et de tours CR-21 aux fins d'observations micrométéorologiques pour appuyer les méthodes utilisées actuellement en pépinière et mettre au point un modèle intégré de calendrier d'irrigation.
- De nombreuses études régionales sur la croissance et le développement en cours, partout en Ontario, intègrent le climat à la planification de la gestion forestière opérationnelle. Dans certains cas, notre ministère a mis au point une nouvelle technologie informatisée TRIM afin d'améliorer nos connaissances sur la croissance et le développement.
- Notre ministère participe également à une multitude d'études relatives au climat afin de prévoir la productivité forestière ainsi que les options de traitement possible. Par exemple, en raison des complexités climatiques qu'on observe dans toute la province de l'Ontario, nous irriguons les vergers à graines dans le Nord-Ouest, tandis que dans d'autres régions du Nord, nous assumons les coûts de drainage des terres forestières afin d'en augmenter la productivité.
- Les pertes de ressources forestières ou leur appauvrissement sont une grande source d'inquiétude pour n'importe quel organisme forestier. Comme je l'ai dit, notre ministère collabore étroitement avec d'autres organismes, particulièrement dans les secteurs 1) de l'incendie, où les prévisions de conditions météorologiques favorables aux incendies ont permis d'épargner des ressources forestières considérables; 2) des insectes et des maladies, où la définition de la «fenêtre» climatique pour une pulvérisation efficace est extrêmement importante; 3) de la pollution de l'air, où l'atmosphère est encore, naturellement, une source majeure de préoccupation en gestion forestière à long terme. Dans ce contexte de croissance, de développement et de pertes, la forêt doit aussi s'adapter au changement climatique à long terme.

Pour le forestier travaillant sur le terrain, on doit élaborer des stratégies de gestion forestière en Ontario en tenant compte de ces complexités climatiques dans le contexte de la «vieille» forêt productive et de la «nouvelle» forêt régénérée.

Notre capacité à stocker biologiquement des ressources futures en bois «sur souche» dépend des contraintes climatiques dominantes partout en Ontario. Les climats rigoureux du Nord créent des défis particuliers pour la récolte et le transport du bois aux scieries. Or, même s'il lui faut travailler dans ces climats, l'Ontario doit demeurer solidement compétitif sur le marché international.

On doit également considérer les exploitations intégrées de nos ressources forestières et explorer de nouvelles initiatives. La production de bois n'est que l'un des nombreux bénéfices offerts par la ressource forestière de l'Ontario. Dans les secteurs des loisirs de plein air et de la gestion de la faune et des pêches, le climat joue aussi un rôle important.

Les efforts conjugués du milieu universitaire, du gouvernement et du secteur privé sont nécessaires pour atteindre ces objectifs. Il n'y a pas de solution facile, mais l'atelier d'aujourd'hui est un premier pas dans la bonne direction.

Une fois encore, bienvenue en Ontario et je vous souhaite d'être bien «acclimatés» à la fin de cet atelier.

CLIMATE AND FOREST RENEWAL

Session I. Climate Applications in Seed and Stock Production

Seed Orchards and Breeding Halls

Greenhouse Environments

Nurseries

Summary

Session II. Climate Applications in Forest Regeneration

Site Selection, Planting Strategy, and Site Preparation

Survival and Growth Following Outplanting

Summary

Discussion

Climate in Forestry — An Introduction

Kurth L. Perttu

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Abstract

Most forestry research and operational practices depend on different meteorological and climatological results. Therefore, forest meteorology/climatology must direct attention to many forestry concerns. The objective of this paper is to present a summary of the most important meteorological elements and their influences particularly on forest renewal and production. Most of the results are obtained from investigations in Sweden, but similar research conducted in other countries has had an obvious influence over the years. The investigations can be divided into general climate, local and microclimate, and bio- and micrometeorology. At latitudes north of 50°, temperature is often the most limiting factor for establishment and growth of forests. Many empirical formulas have been developed to explain either the temperature influence itself or some other closely related variable. Length of growing season, heat sum, growth unit, and respiration equivalent are examples of these expressions. When a forest canopy is removed, the climate is drastically changed, especially close to the soil surface. The frequencies of frost, for instance, usually increase considerably, while evaporation and transpiration decrease, resulting in an increasing soil water content and runoff. By leaving a sparse shelter canopy, the outgoing long-wave radiation decreases, and so the radiation frost risks can be reduced effectively.

Résumé

La plupart des méthodes opérationnelles et de recherche dans le secteur forestier dépendent de divers résultats météorologiques et climatologiques. En conséquence, on doit inclure en météorologie/climatologie de nombreuses préoccupations forestières. L'objectif de cet exposé est de présenter un résumé des plus importants éléments météorologiques ainsi que leurs effets particulièrement sur la régénération et la production forestières. La majorité des résultats ont été obtenus grâce à des recherches effectuées en Suède, mais des travaux semblables réalisés dans d'autres pays ont eu une influence évidente au cours des années. Les recherches peuvent être réparties entre diverses catégories, dont le climat général, le climat local et le microclimat ainsi que la biométéorologie et la micrométéorologie. Aux latitudes supérieures à 50 degrés, la température constitue souvent le facteur le plus limitif pour l'établissement et la croissance de forêts. De nombreuses formules empiriques ont été élaborées pour expliquer soit l'effet climatique lui-même, soit une autre variable étroitement associée. La longueur de la saison de croissance, la chaleur totale, l'unité de croissance et l'équivalent de respiration sont des exemples de ces expressions. Lorsque le couvert forestier est éliminé, le climat change radicalement, surtout près de la surface du sol. La fréquence des gelées, par exemple, augmente considérablement en général, tandis que l'évaporation et la transpiration diminuent, entraînant un accroissement de la teneur en eau dans le sol et du ruissellement. En laissant un couvert-abri forestier clairsemé, le rayonnement à ondes longues ascendant est réduit, diminuant effectivement les risques de gelée de rayonnement.

Background

The most important environmental factors for forest renewal and production are different climatic elements, such as solar radiation, temperature, precipitation, and wind. Depending on where the forest land is situated and what biological factors are considered, the main climatic elements play different roles in the establishment and growth of forests. Most of the solar radiation is converted into heat at the earth's surface, thus creating the different climatic regions. The heat is distributed over the globe under the influence of topography, distribution of sea and land, rotation of the earth, etc. The visible part of radiation is used for photosynthesis (0.1–2%). The result of all these processes is a very complicated pattern of different vegetation zones, which can be identified according to the main climate elements. These climate elements also generally show extreme effects; for example, lack of precipitation causes deserts, and low temperatures cause tundras, etc.

The aim of this introductory paper is to demonstrate how some important climate factors influence the establishment and production of forests, especially in cool climate regions, such as parts of North America and Scandinavia. A short presentation is given on how temperature, precipitation, and light vary in typically maritime (Portland, Oregon, USA) and continental (Montreal, Quebec, Canada) climates, and how the latitude, in some cases, plays a secondary role (Stockholm, Sweden). Data for this comparison is taken from a World Meteorological Organization (WMO) Technical Note (1971).

Portland and Montreal are situated on the same latitude, whereas Stockholm lies considerably farther north. All three cities are almost at sea level. The approximate length of the growing season is similar in Montreal and Stockholm (despite the difference in latitude) but much longer in Portland (Table 1).

Normally, the monthly average air temperature does not fall below 0° in Portland. The annual mean temperature is +11.6°C (Fig. 1). The lowest mean monthly winter temperature is about -10°C in Montreal and about -4°C in Stockholm. The annual mean temperatures, however, are almost the same at these two locations, 6.6°C, respectively (Table 1).

TABLE 1. Locality and growing season data (daily mean temperature exceeding +5°C) from the three cities compared.

			Growing season				
Location	Latitude	Altitude	Dates (day/month)	Length (days)	Annual mean temp. (°C)	Annual precip. (mm)	sun-shine (h)
Portland	45°36'	12 m	5/2 - 20/12	310	11.6	944	2039
Montreal	45°28'	30 m	10/4 - 25/10	195	6.7	971	1880
Stockholm	59°21'	11 m	20/4 - 30/10	190	6.6	555	1973

Montreal receives a practically constant amount of precipitation throughout the year, about 80 mm/mo (Fig. 2). Stockholm has very dry springs but relatively wet late summers. In Portland, July and August are normally very dry, whereas the winter months (November-February) are very wet. The annual precipitation value for Stockholm is only 555 mm, whereas the two North American cities receive about 400 mm more (cf. Table 1).

There are not significant differences between the three locations regarding the amount of light received per year, represented by duration of sunshine (Fig. 3). The daily distribution, however, differs between Stockholm and the two North American cities because of the latitude. Stockholm has more than 18 h of daylight on June 21 compared with about 15 h at the other two locations. The corresponding figures for December 22 are 6 and 9 h, respectively.

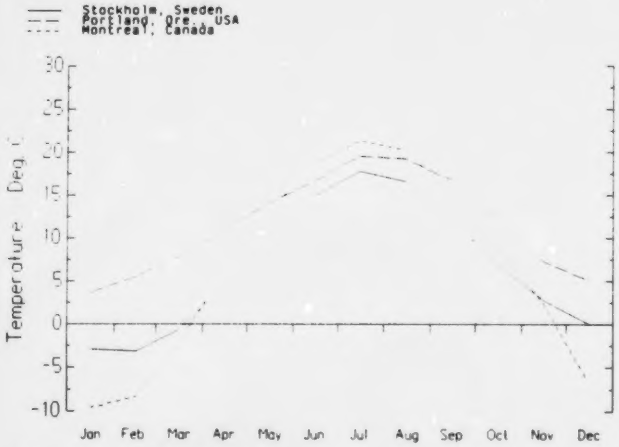

FIG. 1. Normal monthly mean temperatures in Portland, Oregon, USA; Montreal, Quebec, Canada; and Stockholm, Sweden (WMO Technical Note 1971).

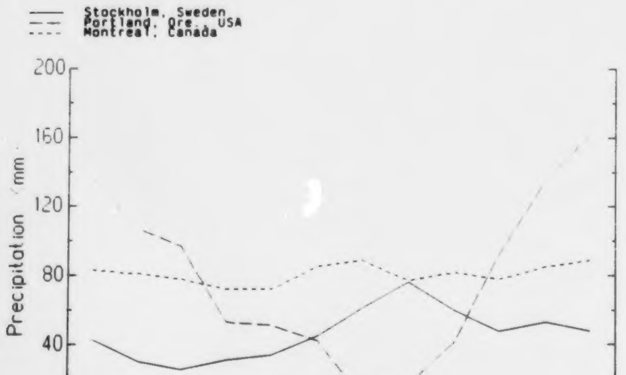

FIG. 2. Normal amount of precipitation in Portland, Oregon; Montreal, Quebec; and Stockholm, Sweden (WMO Technical Note 1971).

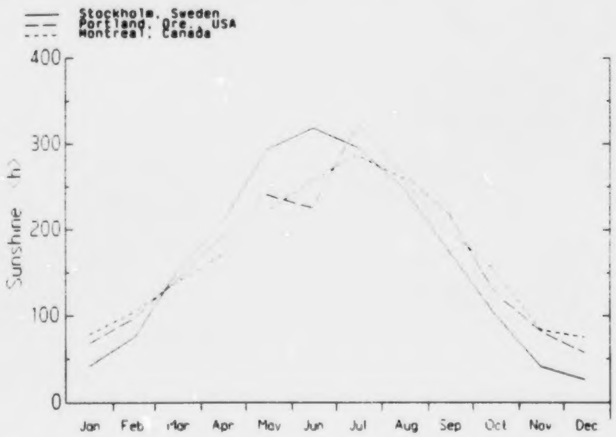

FIG. 3. Normal number of hours of sunshine in Portland, Oregon; Montreal, Quebec; and Stockholm, Sweden (WMO Technical Note 1971).

Material and Methods

The data used for the following calculations have been obtained from the Swedish Meteorological and Hydrological Institute (SMHI), a governmental body responsible for acquisition and storage of databases of basic climate data from the network stations in Sweden. The evaluation of the data has been made in cooperation with the SMHI and the author, and these evaluated data have been made available to Swedish foresters and scientists in the form of tables and maps (Perttu and Huszar 1976, Engsjö et al. 1978, Perttu et al. 1978, Odin et al. 1983).

A considerable part of these climate data has been used within the coniferous forest ecosystem research as well as short rotation forestry in Sweden as a complement to the data gathered at the sites concerned. They have been used mainly in different simulation models to generalize the results.

DIFFERENT TEMPERATURE EXPRESSIONS

Temperature is often a limiting factor at latitudes higher than 40–45° (Geiger 1971). Therefore, many empirical expressions have been deduced to explain how the temperature affects different biological processes. Four of those used in Scandinavia are lengths of growing season, temperature sums expressed in day-degrees, growth units (weighted temperature sums), and respiration equivalents.

LENGTHS OF GROWING SEASON

The length of the growing season in Scandinavia can be expressed as a function of latitude and altitude. Langlet (1937) presented a formula for the threshold value of +6°C, that is, when the daily mean temperatures exceed +6°C, based on 416 Swedish and 28 Norwegian climate locations. He found that the length (Y_6) was:

$$Y_6 = 514.18 - 5.85 \bullet L - 0.0736 \bullet H + 0.000365 \bullet L \bullet H \qquad (1)$$

Where L is the latitude in degrees and decimals and H is the altitude in metres. This formula underestimates the length by about 15 d on average (Fig. 4), less in the north and more in the south, compared with observations (Perttu et al. 1978).

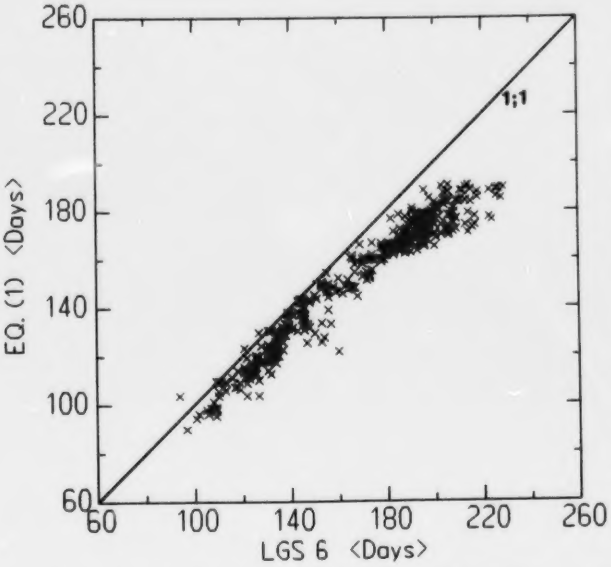

FIG. 4. Comparison between observed and calculated (equation 1) lengths of the growing season for all network stations in Sweden (Perttu et al. 1978).

Later, Perttu (unpublished data) deduced an expression for the length for the same threshold value using data for the inland locations in Perttu and Huszar (1976), that is, locations more than 30 km from the coast:

$$LGS_6 = 676 - 8.28 \bullet L - 0.044 \bullet H \quad (2a)$$

Formula (2a) gives a much better estimate of the length than formula (1), without any systematic deviations from the 1:1 line (Fig. 5).

The observations of the growing season lengths in Perttu et al. (1978) for the threshold values of 5 and 8°C have been used to deduce formulas also for LGS_5 and LGS_8:

$$LGS_5 = 746 - 9.19 \bullet L - 0.049 \bullet H \quad (2b)$$

$$LGS_8 = 592 - 7.32 \bullet L - 0.039 \bullet H \quad (2c)$$

The formulas 2a–c are valid only for average conditions and cannot be used to calculate the length at a single site, unless it does not represent a location with average conditions for the latitude and elevation concerned.

TEMPERATURE SUMS IN DAY-DEGREES

The temperature sum (TS) is by definition the summation of all daily mean values exceeding a chosen threshold value. In Scandanavia, both +8, +6, +5, and +3°C have been used as threshold temperatures. During the last 15 yr, however, the most common value in forestry has been +5°C. Perttu (1983) has presented a formula for the TS (over +5°C) as a linear function of the latitude (*L*) and elevation (*H*):

$$TS_5 = 4835 - 57.6 \bullet L - 0.9 \bullet H \quad (3a)$$

Measured and calculated values show a good correlation, except for a slight overestimation of calculated values around 1000-1200 day-degrees (Fig. 6).

The temperature sums can be deduced for other threshold values. For Swedish conditions, the sums over +6 and +8°C can be expressed by the following equations:

$$TS_6 = 4311 - 52.0 \bullet L - 0.8 \bullet H \quad (3b)$$

$$TS_8 = 3378 - 41.9 \bullet L - 0.65 \bullet H \quad (3c)$$

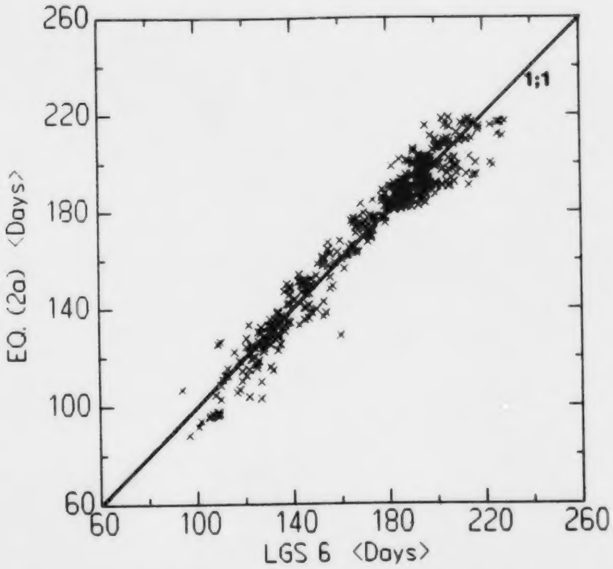

FIG. 5. Comparison between observed and calculated (equation 2a) lengths of the growing season for all network stations in Sweden (Perttu et al. 1978).

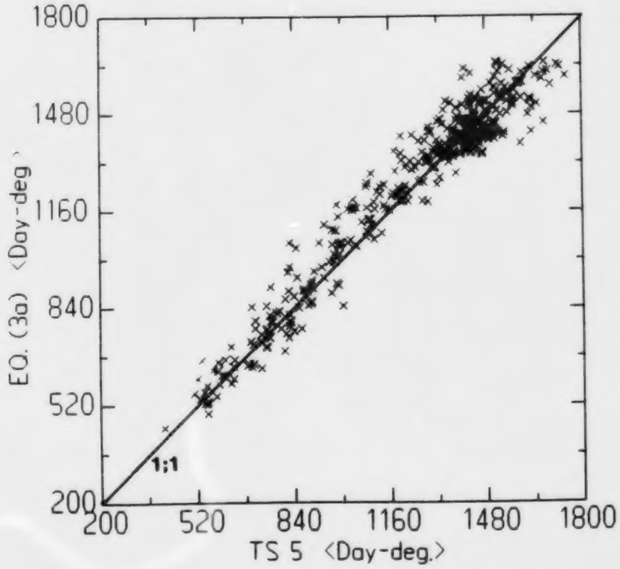

FIG. 6. Comparison between measured and calculated (equation 3a) temperature sums for all network stations in Sweden (Perttu et al. 1978).

For average conditions, the formulas (3a–c) are very useful because they make it possible to apply a simple temperature factor as an input variable, for instance, in the growth models to determine the regional production.

GROWTH UNITS

Growth units are weighted temperature sums in that a higher temperature up to a certain limit contributes more to the sum than a lower one. Mork (1941) derived relations between the growth units (relative top shoot elongation during the second growth phase of Norway spruce, *Picea abies* (L.) Karst.) and the mean temperature of the 6 warmest hours per day. He presented the following equations for the spruce near the timber line in central Norway:

$$G = 0.183 \bullet T_c - 0.479 \qquad \text{for } T_c < 13 \qquad (4a)$$

$$G = 3.85 - 0.475 \bullet T_c + 0.025 \bullet T_c^2 \qquad \text{for } 13 \leq T_c \leq 24 \qquad (4b)$$

where G is the growth unit and T_c is the mean 6-h temperature in Celsius degrees. Similar expressions were given for spruce at lower latitudes. The data from Mork (1941) have been used to deduce an equation for the relation between Mork's growth units and the temperature, but in this case the average 6-h temperatures were replaced by the mean value of the maximum and the noon temperatures, which are more easily available from many stations. This modified equation (Perttu 1983) reads:

$$G' = -0.143 + 3.75 \bullet 10^{-2} \bullet T_v + 1.36 \bullet 10^{-2} \bullet T_v^2 + 1.99 \bullet 10^{-3} \bullet T_v^3$$
$$- 4.09 \bullet 10^{-4} \bullet T_v^4 + 2.30 \bullet 10^{-5} \bullet T_v^5 - 4.00 \bullet 10^{-7} \bullet T_v^7 \qquad (5)$$

where G' is the growth unit as defined above and $T_v = (T_{noon} + T_{max})/2$. The mean difference between T_v and T_c is about 0.3°C.

The values for G' calculated with formula (5) for the inland climate locations in Sweden were used to deduce an expression for the growth unit (GU) as a function of latitude and elevation (Perttu 1983):

$$\text{GU} = Q \bullet (1 - H/H_p) \bullet ((L - L_O)/(L - L_p)) \qquad (6)$$

where H and L are elevation in metres and latitudes in degrees (decimals), respectively, and Q, H_p, L_O, and L_p are coefficients which, for Swedish conditions, have been given the empirical values of 800, 2000, 70, and 73, respectively. With these coefficients, the curves are almost straight lines between latitude 55 and 62°N and the correlation between measured and calculated values is satisfactory (Fig. 7).

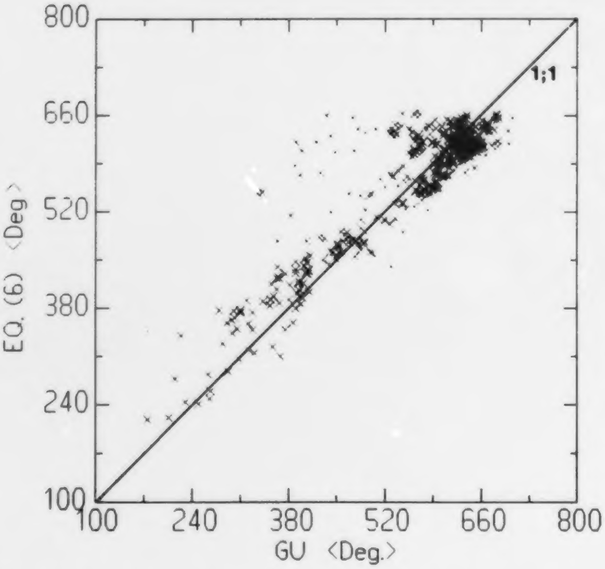

FIG. 7. Comparison between measured and calculated (equation 6) growth units for all network stations in Sweden (Perttu et al. 1978).

RESPIRATION EQUIVALENTS

Dahl and Mork (1959) studied the respiration of spruce as a function of air temperature and found that it increased exponentially with temperature up to a certain limit. The height growth was then found to be proportional to the respiration except for a maintenance level, corresponding to the temperature of +2.6°C. They defined the respiration equivalent (RE) as:

$$\text{RE} = \int T \bullet R_T \bullet \text{dt} \qquad (7)$$

where T is the hourly temperature as a function of time t and R_T is the relative respiration at temperature T. R_T is unity for $T = 10$ C and $t = 1$ h. Using data presented by Utaaker (1963) on R_T in different temperature intervals, the following formula can be presented:

$$R_T = 0.47 - 0.0044 \bullet T + 0.0056 \bullet T^2 \qquad (8)$$

where T now is the hourly mean temperature during the growing season. $R_T = 0$ for $T < +5$°C. By summing the R_T – values calculated for every hour during the growing season, an approximate respiration equivalent can be obtained according to:

$$\text{RE} = \sum_{h=1}^{n} R_T \qquad (9)$$

where h is the hour with temperature T and n is the number of hours during the growing season. A typical value for RE in central Sweden is 6500–7000 units.

COMPARISON BETWEEN VARIOUS TEMPERATURE EXPRESSIONS

There is a good correlation between the various temperature expressions, despite them not representing the corresponding variable. The lengths of the growing season and the temperature sums are both related to the latitude and elevation as shown in equations (2a,b,c) and (3a,b,c) and, therefore, expected to show a satisfactory relation between each other (Fig. 8). Also, the temperature sums and the growth units are rather well correlated (Fig. 9).

Odin et al. (1983) compared annual mean values of RE both with TS5 and GU for 25 network stations in Sweden, ranging from latitude 55.5 to 68°N, from where hourly mean temperatures have been available (Fig. 10a, b). The correlations gave determination coefficients of 0.9783 and 0.9094, respectively.

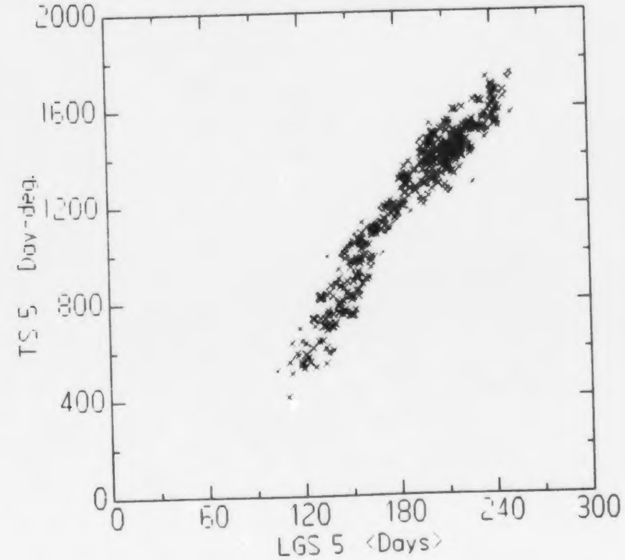

FIG. 8. Relation between observed values of lengths of the growing season and the temperature sums for all network stations in Sweden (Perttu et al. 1978).

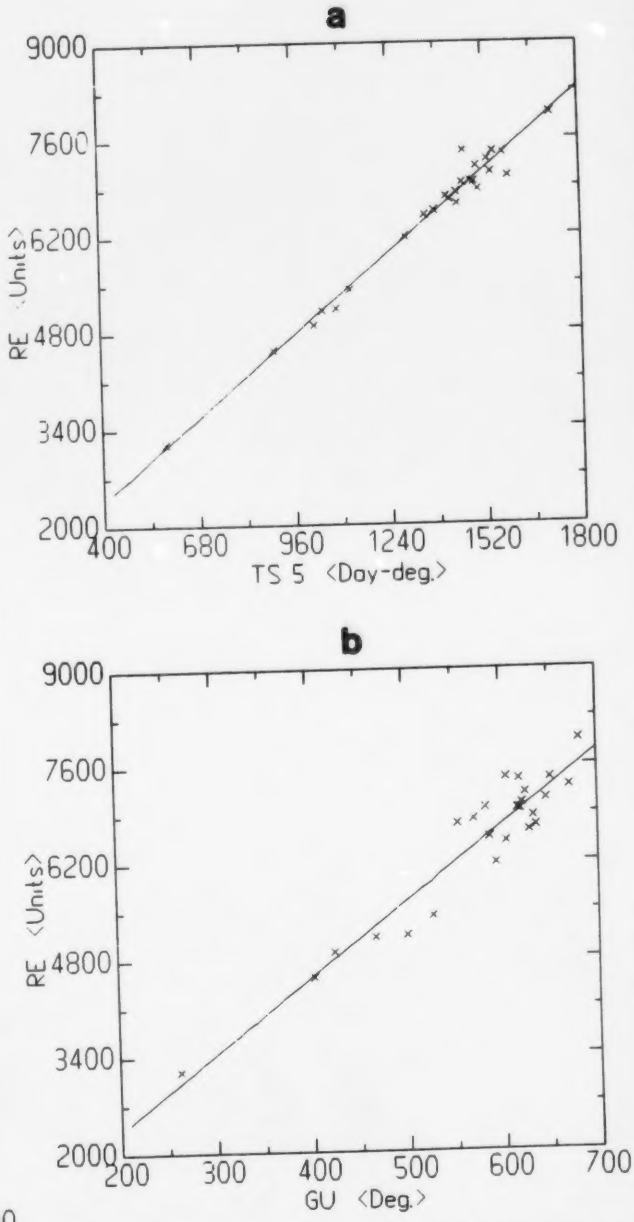

FIG. 10. Relation between observed values of (a) temperature sums and respiration equivalents and of (b) growth units and respiration equivalents for 25 network stations with hourly observations in Sweden (Odin et al. 1983).

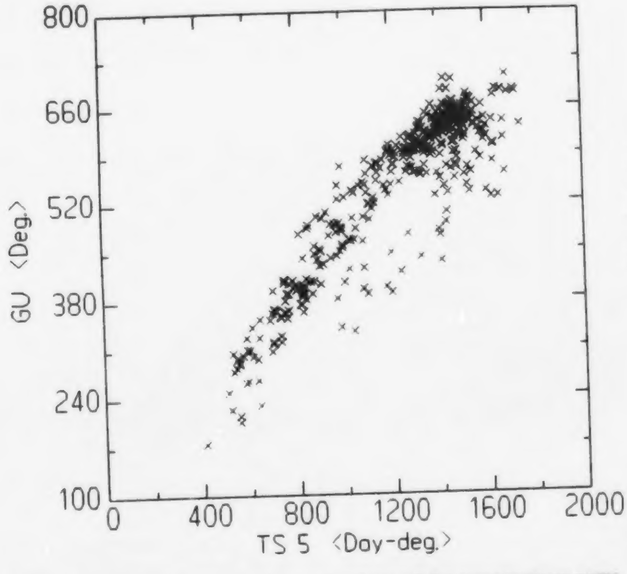

FIG. 9. Relation between observed values of the temperature sums and the growth units for all network stations in Sweden (Perttu et al. 1978).

RADIATION CLIMATE AND FROST

The solar (or short-wave) radiation falling on the earth's atmosphere and surface is largely reflected back into outer space. The rest is either absorbed by the gases and particles in the atmosphere or dispersed to diffuse light, which together with the direct part is absorbed at the earth's surface. The absorbed solar radiation is used for the photosynthetic processes or is transformed into sensible and latent heat. The surface of soil and vegetation then reradiate the heat back into space as long-wave radiation, where it again is partly absorbed, mainly be water vapor and carbon dioxide. Further details about the transfer processes can be found in many textbooks on radiation.

During the night, the short-wave radiation is negligible and only the long-wave part is active. In overcast situations or inside forest canopies, the incoming and outgoing part of this radiation heating or cooling takes place. In clear sky weather on open fields the outgoing long-wave radiation exceeds the incoming, resulting in a cooling of the soil and vegetation surfaces and the air layers close to them. In many places this radiation cooling may cause freezing temperatures, especially during early and late parts of the growing season, when they often damage sensitive parts of the vegetation.

Low temperatures at a certain site are a result of one or both of two main processes, namely advection and long-wave reradiation. Advective frost is caused by a cold airmass moving over the location concerned, and such frosts are not easily avoided. Often they are caused by a thick layer of cold air entering a large area around the site of interest. Radiation frost is only local, and there are different methods of reducing its consequences (for example, WMO Technical Note 1969).

One of the most critical factors in forestry is a satisfactory renewal after harvesting a stand. Many sites turn into frost pockets after cutting, where radiation frost often is reinforced by accumulation of cold air from the surroundings. In such expected situations, a shelterwood should be left instead of clearcutting. To find out how a shelterwood could be designed, Perttu (1981) introduced a sky obscuration factor (SOF), defined as the fraction of sky obscured by vegetative elements for all zenith angles and azimuths. From a long series of radiation measurements in different types of stands in Sweden, he deduced a formula for the reduction of the radiation cooling rate (RED) as a function of SOF according to:

$$\mathrm{RED} = (1 - 0.98 \bullet (\mathrm{SOF})^{0.6} + 10^{-1.7 \bullet (\mathrm{SOF})})/2 \qquad (10)$$

SOF was determined from fish-eye photographs taken upwards below the canopies and evaluated by means of a diode-array scanner (Olsson et al. 1982). Using these methods, the radiation cooling rate is reduced by 50% when SOF is 0.2 and by 80% when SOF is 0.5 (Fig. 11).

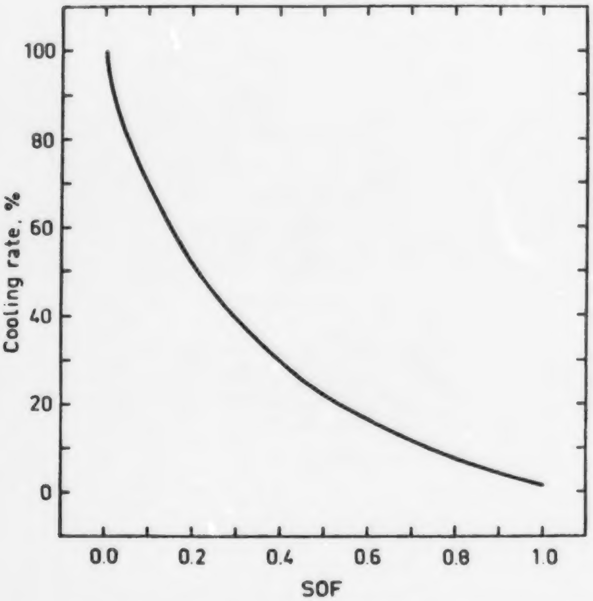

FIG. 11. Reduction of the radiation cooling rate as a function of the sky obscuration factor (SOF) compared to open field (Perttu 1981).

CLIMATE AND ENERGY FOREST GROWTH

Energy forests in Sweden consist of short-rotation stands of mainly *Salix* and *Alnus* species, intensively managed to reach high production levels. Annual yields of 15-20 tonnes dry matter (DM) stemwood per hectare are often available in unstressed willow stands, but even higher figures have been obtained in intensively treated experiments. Alders give somewhat lower annual productions and they are also slow starters compared with willow.

There are several means of relating climate to growth. One efficient way is to use simulation models, where all the equations, variables, and parameters are organized logically to facilitate the use of models. During the last 6-7 yr, mathematical simulation models have been used in Swedish energy forestry to determine the growth pattern and the production level. The most important factors are solar radiation, air temperature, water, and nutrient status. In the photosynthetic processes, the carbon from the atmosphere is transformed into biomass under the influence of light and the leaf nitrogen. Part of the light falling on the canopy is reflected, whereas the rest is absorbed when penetrating downwards in the crown. The extinction of light is dependent on vegetation stucture and on the wavelength and type of light. Diffuse light from the sky penetrates deeper in the canopy than direct sunlight (Eckersten, 1984). To estimate the carbon uptake by the vegetation, it is necessary to know the light intensity and the amount of leaves at different depths in the canopy. Considering also the carbon loss by respiration and the temperature influence, it is then possible to calculate the biomass growth. The development of the growth model concept during recent years has been published in several reports, Eckersten et al. (1983), Nilsson and Eckersten (1983), Perttu et al. (1984), Eckersten et al. (1987). A book on modelling is under publication by PUDOC, Wageningen, The Netherlands (Perttu and Kowalik 1987).

Using this growth model, annual willow production has been simulated for 16 locations distributed throughout Sweden (Perttu et al. 1984). Comparing these figures with the temperature sums at the same places revealed a linear relationship according to:

$$Q = -9.09 + 0.0178\ \mathrm{TS5} \qquad (11)$$

where Q is either the 1st yr above ground production (stems and leaves) or the 2nd or 3rd yr stem wood production. The reason is that the 1st-yr stems after each harvest grow about 35% less than older stems because of later leaf development during the 1st yr. This difference corresponds approximately to the amount of leaves.

Combining equation (11) with (3a) gives the follwing expression for the regional production as a function of latitude and evaluation:

$$Q = 77.0 - 1.03 \bullet L - 0.016 \bullet H \qquad (12)$$

Again, several of these equations are valid only on a regional basis and cannot be used to compare individual sites, where the micro- and local conditions must always be taken into account.

Discussion and Conclusions

There are several different climate variables or expressions than can be used when describing the biological processes, such as growth. The equations discussed have both advantages and disadvantages. The length of the growing season, which by definition is controlled by the daily mean temperature, gives a reasonable idea of when the processes will take place. The growth units, which are weighted temperature sums, are sometimes better expressions when explaining growth relations than the linear temperature sums. The respiration equivalent requires hourly mean temperature, which normally is available only at a few network stations (about 10% in Sweden). This expression is, therefore, less useful when calculating the production on a regional basis. If measurements of these temperatures are available, the respiration equivalent is frequently a suitable variable. In most cases the simple temperature sum seems to be the best and easiest available temperature expression that can be used for many purposes when describing biological processes.

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Importance of Climate in Selection of Genetic Resources

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Abstract

Tree growth can be greatly influenced by a wide range of climatic factors. The rate of climatic change is relatively slow compared with the generation time of forest trees, so the potential exists for selective adaptation to these climatic influences. The interaction of natural selection with other genetic forces will result in genetic variation in response to climatic variables.

Clearly, this genetic variation must be considered in the selection of genetic resources for the tree improvement component of a forest renewal program, both for exotic and native species. This paper outlines the population genetics principles involved in the response of forest trees to climatic factors and provides examples of genetic selection programs in which climatic considerations are important. The examples are drawn from different forest regions and involve both large- and small-scale variation.

Résumé

La croissance des arbres peut être considérablement modifiée par une vaste gamme de facteurs climatiques. Comme l'évolution climatique est relativement lente si on la compare à la durée de génération des arbres forestiers, ces derniers ont une capacité potentielle d'adaptation sélective aux influences climatiques. L'interaction de la sélection naturelle avec d'autres forces génétiques produit la variation génétique en réaction aux variables climatiques.

Il est donc évident que cette variation génétique doit être prise en considération dans la sélection des ressources génétiques pour la composante d'amélioration des arbres dans un programme de régénération forestière, que les espèces soient exotiques ou indigènes. Cet exposé offre un aperçu des principes de génétique de population qui entrent en jeu dans la réaction des arbres forestiers aux facteurs climatiques et fournit des exemples de programmes de sélection génétique où les considérations climatiques tiennent une place importante. Les exemples sont tirés de diverses régions forestières et comportent des variations à grande et à petite échelle.

Introduction — Evolution and Genetics

Ever since the development in the last century of the "modern synthesis" of evolutionary theory as a result of the work of Darwin, Wallace, and others, it has been recognized that the "fitness" of an individual is determined by its ability to both survive and reproduce. Such demands on an individual obviously require that it be physiologically well-adapted to survive and to reproduce in its existing habitat or environment. In the case of plants, the environment consists of two components, the lithosphere, or edaphic environment, and the troposphere, or atmospheric environment (Larcher 1975).

Climate is " . . . the collective state of the atmosphere at a given place or over a given area within a specified period of time" (Landsberg 1945). Because the rate of climatic change, on an annual basis, is relatively slow compared with the generation time of forest tress, the potential exists for adaptation to climatic conditions. Furthermore, because there is spatial variation in climate, it can act as a selective force, tending to produce and maintain genetic variation among individuals and among populations of individuals. The extent to which the climate determines patterns of genetic variation will depend on factors such as the relative strength of other genetic forces and the population structure and mating system of the species.

It has long been recognized and reported that climatic factors can act as "isolating mechanisms" (Dobzhansky 1937) in the process of speciation and the maintenance of species integrity. For example, Shreve (1915) demonstrated that temperature minima were critical in determining the distribution of the cactus species *Cereus giganteus*. However, many nonclimatic factors can also act as isolating mechanisms. In the case of allopatric species, physical barriers may often be responsible for species separation. Such is the case in many well-known examples of unique animal and plant species confined to individual islands. In the forestry context, an ocean and a continental land mass act as physical barriers separating Sitka spruce (*Picea sitchensis* (Bong.) Carr.) from regions of northwestern Europe to which it is physiologically well-adapted. Similarly, many eucalyptus species have proved to be adapted to a wide range of subtropical climates from which their natural range is isolated by oceanic barriers.

The decision to use artificial regeneration in a forest renewal program automatically allows the option of genetic selection of the propagules used in regeneration. At the species level, the opportunity is obvious — in addition to Sitka spruce and the eucalypts already cited there are many examples worldwide of introductions of exotics that are more productive than native species. In such cases climatic, as well as edaphic, factors play a major role in the selection of genetic resources and the consequent success of introductions. The long history of genetic selection in agricultural crops is well established, but it is noteworthy that introduction and selection of forest trees is also not a recent development. Thus, when the Romans introduced the European sweet chestnut (*Castanea sativa* Mill.) to Britain, they had to select for survival and growth in suboptimal climatic conditions, whether they realized it or not.

For native species, it might seem logical that if a population of individuals was present in a particular locality for many generations, then individuals from that population should be best adapted for the local environmental conditions. This certainly may be true but, for reasons that will follow, is not necessarily so. In any case, whether local or nonlocal material is used for a forest renewal program, genetic testing will be required, resulting in selection of the most suitable genetic resources. The importance of climatic factors in this process will be described in three sections. Firstly, the extent of climatic effects on genetic variation will be summarized. Secondly, the mechanisms of development and maintenance of genetic variation will be described and, finally, the implications for selection and genetic improvement programs will be discussed.

Climatic and Genetic Variation

A "common garden" approach was used by Turesson (1922, 1923) to study the genetic basis for variation in plant characters in relation to ecological factors. He termed these studies "genecology" which, in its most general meaning, is the study of the adaptive properties of any sexual population in relation to its environment (Langlet 1971).

Clearly, genecological studies are an essential first step in any genetic improvement program and, as a result, a vast amount of information has been accumulated over the past 50 yr on the relationship between growth characters and environmental variables for many commercial forest species. Turesson defined individuals exhibiting some genetically inheritable characters in response to particular environmental conditions as constituting an "ecotype." Subsequently, Huxley (1938) defined a "cline" to be a pattern of variation in which there is a gradation of some character over space. Strictly speaking, a cline need not be genetically based, nor related to variation in an environmental variable, but it is usually used in such a context. The two terms have therefore come to represent alternative possible patterns of genetic variation in response to a variable environment, producing either a disjunctive or a predictable pattern of genetic variation, respectively.

When outlined in these terms, genecology may appear to pose relatively few problems. Simply sampling populations of a species, collecting relevant ecological data, and growing the samples in a common environment should indicate the existence of a cline or of ecotypes and the determining environmental factors. In practice, however, many problems, many related to sampling, arise. In the sampling of populations, it will not usually be practicable to sample populations from a species with a wide distribution at satisfactory intensity. Consequently, clines may be obscured due to the inadequacy of the sampling, giving rise to the impression of ecotypic variation. Sampling in a north-south transect may fail to reveal a cline operating in some other direction due to elevation or distance from a coast. As a result of the configuration of the North American continent and the pattern of atmospheric flow, isotherms in northern and central Ontario run northwest to southeast, instead of west-east. Therefore, in such a region, a thermoperiodic response can be distinguished from a photoperiodic response, whereas in other regions the two are confounded. In any case, a cline in one economically important character may be a response to a different environmental variable than that for another character. In loblolly pine (*Pinus taeda* L.), height growth is related to distance from the coast, but there appears to be an "ecotype" that is resistant to fusiform rust (*Cronartium quercuum* ssp. *fusiforme*) and does not seem to be related to any climatic or edaphic factor (Wells and Wakeley 1966). The tree breeder then must successfully combine these two patterns of variation. Just what is the difference between a cline and an ecotype? Intensive sampling of the boundaries of an ecotype may indicate that they are simply areas where the slope of clinal variation is very steep (Langlet 1959).

Despite all these potential problems in the design and interpretation of genecological studies, much valuable information has been obtained. In many north temperate species, the timing of spring flushing appears to be related to thermoperiod or, more specifically, accumulated heat sum (Morris et al. 1957, Lines and Mitchell 1966, Sucoff 1971). Northerly seed sources generally require lower heat sums before flushing. However, Cannell and Sheppard (1982) found that for Sitka spruce growing in Scotland, southern provenances actually required a lower heat sum before beginning the dehardening process of the old tissues and, therefore, did so earlier than northern provenances. Despite this, there was no significant difference in flushing time or in frost susceptibility at time of flushing among provenances. Also, the heat sum required to cause bud-burst partially depends on the length and severity of the chilling period (Cannell and Smith 1983). The anticipated global increase in mean annual temperature (Hansen et al. 1981) would thus certainly affect the time of bud-burst, but the direction would depend on existing chilling requirements. Cannell and Smith (1986) predict that for Sitka spruce in Scotland, with a 2°C increase in spring temperatures, the balance between earlier accumulation of heat sums and the increased heat sums required as a result of decreased chilling would lead to flushing time only 5 d earlier than at present. In such circumstances, although the genetic variation in flushing time may be largely additive (Eriksson et al. 1970), thus permitting effective genetic progress through selection, it is probably not currently worthwhile to select for abnormally late flushing provenance or genotypes.

Just as the start of the active growing period is determined by the temperature regime, late summer and autumnal hardening of the tissues must be timed so as to avoid susceptibility to potentially damaging autumn frosts and low winter temperatures. Obviously, in the northern hemisphere, material from northern sources will be adapted to an earlier onset of dormancy than more southerly sources. Due to the generally close association of earlier autumn frosts with increasing latitude, a photoperiodic response is often demonstrated in genecological tests for budset and hardening. Because of earlier autumnal damaging frosts at northern latitudes, northern sources set bud at longer daylengths than southern sources (Wareing 1956, Nienstaedt 1974, Ekberg et al. 1976). Although budset and the onset of tissue hardening is largely a response to declining photoperiod, the subsequent rate of tissue hardening depends on thermoperiod (Jonsson et al. 1981). A prolonged spell of mild temperatures will delay tissue hardening, whereas warm long nights followed rapidly by cold long nights will greatly accelerate the hardening process. Furthermore, temperature control of tissue hardening appears to be far more significant in southern provenances, compared with more northerly seed sources which may be largely independent of thermoperiod (Cannell and Sheppard 1982). As a result of these factors, the growth period for northerly sources is shorter than that for more southerly sources. In a species with both an inland and a coastal distribution, however, "photoperiodic ecotypes" have been postulated that enter dormancy at different times at the same latitude (Vaartaja 1959). These results obviously have important implications for height growth and survival and, therefore, the selection of genetic resources. This is especially true as budset and autumn frost hardiness, in addition to flushing time, have been shown to be largely under additive genetic control (Erikson et al. 1970, Norell et al. 1986).

In mature north temperate conifers, annual shoot extension occupies only a short period early in the growing season, but is partially fixed in the previous growing season by the number of stem units in the overwintering bud (Cannell et al. 1976, Pollard and Logan 1976). Height growth thus depends on both the number of stem units initiated and the amount of extension of each stem unit. Within a given environment, the amount of stem unit extension appears to be relatively uniform within a species (Lanner 1976), so the important quantity is the number of stem units initiated which, in turn, depends on the rate and duration of initiation (Cannell et al. 1976). The importance of these two factors varies with genus. In pines, provenances differ in their maximum rate of stem unit initiation, whereas in spruces the duration of initiation varies (Cannell and Willett 1975). The net result, however, is that for north temperate conifers, southern provenances tend to exhibit greater height growth than more northerly provenances at southern sites. When moved to a more northerly location, though, the requirement of southern provenances for larger heat sum accumulations before flushing may result in a shorter growth period and therefore less height growth. Such considerations have led to various efforts to graphically predict the optimum (usually not the local) seed source for a given site (e.g., Kung and Clausen 1984, Raymond and Lindgren 1986). Such approaches can often lead to valid and valuable generalizations over large areas, but frequently the response of genetic resources to variation in local climate can mask broad trends, making prediction impossible (Morgenstern et al. 1986; unpublished data, Petawawa National Forestry Institute).

The influence of climatic and other environmental variables, especially photoperiod, on many growth characters, has been demonstrated for a wide variety of species. To illustrate the types of results obtained and the problems in interpretation, examples will be given of two species.

Several series of large Scots pine (*Pinus silvestris* L.) provenance tests have been initiated since 1908 by IUFRO and other agencies. These have generally shown a north-south trend in height growth and seed size, and needle length, succulence, and color, in response to daylength and temperature gradients (Wright 1976). However, both height growth and needle length tend to decrease again in the southern part of the range. Stern and Roche (1974) noted that in regions of summer drought, bud initiation may cease in midsummer due to a combination of heat and moisture stress. In the Mediterranean climate, at the southern limit of the European range of Scots pine, such conditions are common. This could explain the reversal of the expected trend for seed sources from southern regions.

Based on results from a 1938 IUFRO provenance test in New Hampshire, Wright and Baldwin (1957) classified European Scots pine into 11 geographic ecotypes based on growth rate, stem and crown form, survival, and susceptibility to pests. However, reanalyzing the data, Langlet (1959) demonstrated a continuous (clinal) pattern of variation. These contrasting results from the same data illustrate the problems associated not simply with sampling, but also with interpretation.

Many traits have been studied in white spruce (*Picea glauca* (Moench) Voss) provenance tests. Generally, results have indicated clinal variation for height and other growth characters in response to photoperiod, temperature, and precipitation (Nienstaedt and Teich 1972), but no pattern in the variation of other characters such as specific gravity (Holst 1960). Superimposed on the simple pattern of clinal variation in height growth, however, is evidence of some ecotypic variation. For example, provenances from much of eastern Ontario have ranked near the top in many tests from the Lake States to the Maritime provinces (Nienstaedt and Teich 1972; Murray and Skeates 1985). There is no definite evolutionary explanation of this regional superiority. Farrar and Nicholson (1967) also postulated the existence of an ecotype adapted to growth on calcareous soils.

Climate and the Maintenance of Genetic Variation

As noted earlier, provenance tests are an essential component of a tree breeding program. However, they are costly to establish, time-consuming, and usually take several years to produce useful results. In many cases, therefore, sampling is concentrated on anticipated areas of interest. Consequently, the results obtained are often largely applicable to only a restricted area and may be of little use in predicting nonsampled populations (as discussed earlier). This requires an understanding of the mechanisms involved in the establishment, maintenance, and change in genetic variation (evolution) for the species.

The study of genetic variation in a genetic or Mendelian population is termed population genetics. We can consider such a population to be a collection of freely intermating individuals, or genotypes, and is characterized by the allele (gene) frequencies of the total "gene pool."

Four genetic forces can act to change allele frequencies, for example, to cause the evolution of a population (Harlt 1980). The source of all new genetic variation is mutation which, however, usually occurs at a very low frequency. The two most important genetic forces are selection and migration. In selection, some external factor acts so as to favor some genotypes over others, either in terms of survival or reproductive success. The result will be a tendency for one or a few genotypes to become more common, whereas others approach extinction. Obviously, climatic factors can act as major agents of selection. A prime example has already been discussed — the adaptation of flushing and dormancy to temperature and photoperiodic influences, respectively. Individuals that flush particularly early will either be killed by frost, or become so stunted by repeated injury to new shoots that they succumb to more conservative but successful competitors. Similarly, individuals that set bud and enter dormancy early or that initiate stem units relatively slowly, will be overtopped by more vigorous individuals.

Migration is the movement of alleles, in the form of individuals, zygotes (seeds), or gametes (pollen), from one population to another and will tend to result in similar allele frequencies among populations. Again, climatic factors play a major role. Wind-borne tree seed can travel long distances in windy regions or where extensive snow cover persists for long periods. Conversely, in areas where there are extreme local variations in climatic conditions, such as mountainous regions, migration of gametes by pollination may be prevented due to phenological isolation of populations. This is clearly demonstrated by comparing studies on a mountain species and lowland species from the same genus. Linhart et al. (1981) detected significant differentiation among groups of ponderosa pine (*Pinus ponderosa* Laws.) over distances less than 100 m in the Colorado Rocky Mountains. This they attributed to selection in a heterogeneous environment on a local scale, combined with extremely restricted gene flow (migration). On the other hand, studies of various other pine species from far more uniform climates and environments have demonstrated a much lower level of variation among populations, even over distances of hundreds of kilometres (Yeh and Layton 1979, Guries and Ledig 1982, Danzmann and Buchert 1983).

The final genetic force is random drift, which is important in small populations where, by random chance, not all genotypes will contribute equally to the gene pool of the next generation. In species that tend to form small, isolated populations, or at the extremes of the range of a species, drift can result in random variation among populations, which could be interpreted as evidence for ecotypes. Another consequence of small population size is inbreeding, which is not a genetic force because it does not alter allele frequencies. It does, however, result in an increase in the frequency of homozygotes. Most north temperate forest species, except for red pine (*P. resinosa* Ait.) (Fowler and Morris 1977), exhibit inbreeding depression. Therefore, again, sampling of small populations could indicate an exception to the general pattern of variation. Even in large populations, the number of individuals contributing to a mating event may be quite restricted in some years, so that even though the actual population size is large, the "effective population size" is small. Heavy flowering appears to be a response, in part, to meteorological events at the time of flower bud initiation (Lowry 1966). Following a cool, damp summer, the number of individuals flowering will often be small. The amount of inbreeding characterizing the "mating system" therefore varies from year to year and site to site, introducing apparent temporal and spatial variation in characters subject to inbreeding depression. Individuals in severely inbred populations tend to have high levels of homozygosity. This, combined with the attendant low migration rates, results in a slow response to a change in genotypic fitnesses, due to the low genetic variation. Therefore, inbred species such as red pine and small, inbred populations of other species will react more slowly to changes in selective forces (for example, through climate change) than outcrossed species and populations. They may therefore be less well adapted than outcrossed genetic resources to current environmental conditions.

The interaction of the above genetic forces, the mating system, and the population structure will result in the observed variation pattern. Where photoperiod and temperature exert a comparatively strong selective force in relation to rates of migration, a roughly north–south cline will be detected. Such is the case for the coastal variety of lodgepole pine (*Pinus contorta* Dougl. ssp. *contorta*). However, some coastal populations from the Skeena River area, Lulu Island, and elsewhere exhibit various morphological characters that are intermediate between coastal and inland subspecies. The cause of these anomalies in an otherwise simple clinal variation pattern has been attributed to various factors. These included the influence of different selective forces on local edaphic "inlandtype" sites (Lines 1968), increased opportunity for gene flow where the two species are geographically proximate, or the persistent effects of postglacial species migration (Wood 1955). Certainly, whenever another selective agent such as local edaphic conditions becomes significant, an ecotypic pattern of variation may develop.

Climate and Tree Breeding Implications

The previous two sections have indicated the importance of climate in the development and maintenance of genetic variation. Clearly, therefore, a consideration of climate is very important in the selection of genetic resources. This is most obviously illustrated in the selection of material for a forest renewal program involving an exotic species. In the United Kingdom, for instance, sources of Sitka spruce and lodgepole pine for use in a particular area can be based to a large extent simply on a comparison of the climate with that of the Pacific coast of North America. This is true, however, only as long as the tree breeder is aware of the potentially complicating factors such as locally abnormal climatic conditions, the effect of other selective agents producing local ecotypes, the possibility of contamination through migration and small population size. Again, the situation is simplified due to the predominantly linear distribution of Sitka spruce (and the coastal variety of lodgepole pine), which largely precludes the possibility of nonparallel clines.

In the case of breeding programs for wide-ranging species in areas of relatively homogeneous climate, the situation is not quite so straightforward. In the Boreal Forest Region of Canada (Rowe 1972), for example, a general trend in response to photoperiod and temperature can usually be demonstrated, but other selective agents such as edaphic factors, together with migration and population size, can also be highly significant. The result is that certain provenances may prove to be superior when planted over a wide area. Such is the case with white spruce, as described earlier; black spruce (*Picea mariana* (Mill.) B.S.P.) for which provenances from northwestern Ontario perform well at more easterly and southerly sites (Boyle 1985); and for jack pine (*Pinus banksiana* Lamb.) in which certain Quebec provenances grow well throughout northern Ontario and Quebec (Yeatman 1984). Similarly, the glacial distribution and postglacial migration of a species can have a lasting effect. A postglacial genetic bottleneck has been suggested as the reason for high levels of homozygosity and little local adaptation in red pine (Fowler 1965, Fowler and Morris 1977), and the migration route of Norway spruce (*Picea abies* (L.) Karst.) may explain the inferiority of southern Swedish sources compared with Polish provenances (Krutzsch 1974). Finally, the effect of climatic change must be considered. Although the generation time of forest trees is sufficiently short that adaptation to existing climatic conditions is possible, the potential rate of climatic change is such that forest tree populations may be optimally adapted to climate conditions that have since changed. This is certainly far more possible in forest trees than for outcrossing herbaceous and crop species that have shorter generation times.

Whatever the distribution and population structure of the species, the tree breeder is faced with the problem of selecting genetic resources from a spatially variable gene pool for use in a spatially heterogeneous environment. A genotype, family, or population sample that performs consistently well in a wide variety of environments is termed "stable," in contrast to those that perform well only on particular sites, which are "unstable." Ideally, to minimize the amount of effort required in a breeding program, the tree breeder would hope to select a high-yielding, stable genotype. Unfortunately, this requires maximization of the effort required in the selection and testing program and is therefore rarely possible. Although, as noted previously, stable, high-yielding provenances have been identified in several boreal species, there are usually higher yielding, unstable provenances for any site, and the same is true at the genotype level. The breeder is therefore faced with the choice between a relatively simple improvement program, designed for suboptimal genetic gains, or a highly sophisticated and consequently more expensive program to give the best results possible. The usual solution to this dilemma, of course, is some form of compromise.

Most operational tree improvement programs initially delineate "seed zones" to prevent the distribution of seed outside defined environmental limits (deployment zones). These seed zones are usually based on ecological and climatic information, suitably adjusted for administrative or other environmental considerations. Once genecological and population genetics information is available, "breeding zones" are defined within which a particular set of stable genotypes is established to provide propagules for reforestation on all sites suitable for that species. Within a single region, breeding zones wil not usually be coincident for different species. To maximize genetic gain, these breeding zones are generally designed to be as small as is administratively and economically feasible. One reason for this is that if genotypes are selected for a small range of environments, it is obviously possible to select higher yielding stable genotypes than if they are to be used on a wider range of environments. Another reason is that it is possible to subsequently amalgamate propagules from more than one production population (seed orchard) if desired, but it is not possible to divide a production population into two.

Whither Climate and Genetic Selection?

The previous section outlined the current approach toward accounting for climatic variation in the selection of genetic resources. With new approaches and rapidly developing technology, opportunities should exist for more sophisticated exploitation of climatic factors in future breeding strategies.

Certainly, with greater knowledge of the effects of climatic factors on economically important characters, and the relative importance of climate affecting population structure and mating system, it should be possible to make more rapid and efficient genetic selections. A form of index selection, in which information from relative and different assessment ages is used for selection, could be utilized, taking account of controlled environment responses to climatic variables. This could enable not only earlier and more efficient selections, but also selections for nonsampled environments. Again, a greater understanding of the response to climatic factors and interactions with genetic population structure could allow the design of high-yielding stable genotype groups, or clonal mixtures. Whereas certain elements of these mixtures may be most productive in one environment, different genotypes may be best adapted in another. When planted as a mixture over a range of environments, yield per unit area may be optimized, as the less productive genotypes act merely to control competing vegetation and prune the better clones. Alternatively, if genotypes that exploit different environmental factors to different degrees are mixed, the resulting mosaic may be more productive than any single genotype plantation. The development of micropropagation not only permits easier exploitation of specific genotypes, but also potentially provides the opportunity for in vitro selection of particular characters. Rapid screening for reaction to environmental influences is possible and the micropropagation method itself may actually generate new genetic variants for selection — this is termed "somaclonal variation." A prime example of this approach is the screening of callus or cell cultures of some crop plants for salt tolerance by immersion in a saline solution followed by plantlet culture from the surviving callus or cells (Bhaskaran et al. 1983, 1986). A similar example of selection for climatic factors could be screening for absence of physical or genetic damage following exposure to freezing temperatures to identify genotypes for planting on particularly cold sites. Such an approach has already been shown to be feasible in plants such as strawberry (*Fragaria* L.) and wheat (*Triticum* L.) (Dr. K. Kartha, pers. comm.).

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Climatic Restrictions on Stock Production and Potential Solutions

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Abstract

Although the use of greenhouses and container technology can avoid or lessen adverse effects that climate imposes on bareroot seedlings, some major problems remain, particularly overwintering.

Solutions to climatic problems in nursery production include avoidance (e.g., frozen overwinter storage), tolerance and compromise (e.g., production in phase with the growing season), or confrontation using technology to circumvent limitation whenever economically possible (e.g., extended greenhouse culture).

In both bareroot and container nurseries, it is impossible to predict and influence growth and measure the physiological condition of seedlings to produce crops suited to outplanting sites. The use of computers and crop modeling facilitates solving these problems.

The goal is to produce, at acceptable cost, seedlings tailored to perform well after outplanting. Combating climate costs money so optimizing stock production depends equally on economic and technical solutions. Alternate technologies must be justified by postplanting improvements.

Résumé

Bien que l'utilisation de serres et la technologie des plants en récipient permettent d'éviter ou d'atténuer les effets défavorables que le climat impose aux pousses à racines nues, on n'a pas encore réussi à éliminer certains problèmes majeurs dont, en particulier, l'hivernage.

Les solutions aux problèmes climatiques avec la production de plants en pépinière consistent à éviter les difficultés (par exemple l'entreposage de spécimens congelés l'hiver), et à recourir à des mesures de tolérance et de compromis (par exemple la production en phase avec la saison de croissance), ou de confrontation à l'aide d'une technologie visant à repousser les limites du possible en tenant compte des facteurs économiques (par exemple une culture étendue en serre).

Dans les pépinières de plants en récipient et de plants à racines nues, il est impossible de prévoir et d'influencer la croissance ainsi que d'évaluer l'état physiologique des semis afin de produire des plants adaptés aux terrains où on souhaite créer des forêts pérennes. La solution de ces problèmes est facilitée par l'utilisation d'ordinateurs et la modélisation des cultures.

L'objectif consiste à produire, à un coût raisonnable, des semis conçus de façon à donner un bon rendement après la transplantation en forêt. Comme la lutte contre les facteurs climatiques est coûteuse, l'optimisation de la production de plants dépend autant des solutions économiques que techniques. Les technologies de rechange doivent être justifiées par des améliorations de post-transplantation.

Introduction

Severity of local climate is a primary factor in the selection of nursery sites, cropping systems, and cultural practices in nursery production. The choices range from bareroot field crops totally dependent on a climatically defined production window in summer, the production of container stock where the growing season is extended in spring and fall with protective structures, to the use of climate-automated greenhouses in winter.

Climate can be shown to have a twofold effect. In the bareroot nursery the effect is direct: crops must be protected from adverse weather conditions, and prediction of growth and development as a function of outdoor weather is required. In greenhouse culture the effect of weather is indirect: it increases the cost of a container crop. After container seedlings are placed outdoors they are under the same restrictions as a bareroot crop. The various restrictions that climate imposes on the growing seedling are listed in Table 1, adapted from Hudson (1975).

The objective of any forest nursery can be simply stated: It is to produce optimally plantable, survivable seedlings, preferably at minimum cost, in an uncooperative native climate. The study of crop–climate interactions has been the focus of research in agriculture and floriculture over many years, and much of the currently applied forest nursery technology has been transferred from this sector. However, for a variety of reasons, climate has a proportionally greater impact on production in forest nurseries than in agriculture:

1. The high technology forest nursery is a new type of culture compared with established field cropping methods, like those used for wheat or citrus trees, or for high value greenhouse produce, like roses or tomatoes. Often we have less knowledge about, and therefore less control over, the production of forest tree seedlings than of agricultural crops. Although forest nurseries are rapidly expanding in number and size, the total effort in both research and production is still small compared with agriculture. For instance, the total greenhouse area devoted to reforestation in Canada in 1983 was 26.4 ha (Smyth and Brownwright 1984) compared with approximately 500 ha for other greenhouse use (Anon. 1986). Therefore, it is not uncommon to adapt cultural innovations and research from the agricultural sector for use in forestry.

2. Agricultural production is physically located to take advantage of favorable climate, good soil, and major population centers. For example, almost 50% of the entire Canadian greenhouse industry is concentrated around Leamington, Ontario (IBI Group 1979). In contrast, many forest nurseries are located adjacent to the forest region they must supply. These regions are more likely to be marginal or unexploitable for agriculture due to poorer soil and harsher climate. Historically, the best land has often been developed for agriculture.

3. Forest tree seedlings must be conditioned for outplanting in a harsh environment where there is little cultural control except for the comparatively crude measures of site

TABLE 1. Factors of the plant environment (adapted from Hudson 1975).

Above ground	Below ground
Radiant energy	Temperature: With special regard to gradients between different depths
Light: Daylength Spectral composition Intensity	Soil moisture: Amount and availability
Temperature: Seasonal and daily fluctuations Incidence of frost or high temperature	Soil atmosphere composition: Especially $CO_2:O_2$ ratio
Humidity (vapor pressure)	Nutrients: Concentration, balance, and availability of major and minor mineral nutrients
Wind: Average speed Gustiness and turbulence Direction	Soil pH and total salt concentration
Cloud, mist, and fog	Soil character and depth, as it affects air, water, and root growth
Precipitation: Dew, rain, sleet, snow, hail	Soil flora, especially mycorrhizae
Atmospheric composition: Carbon dioxide Pollution	

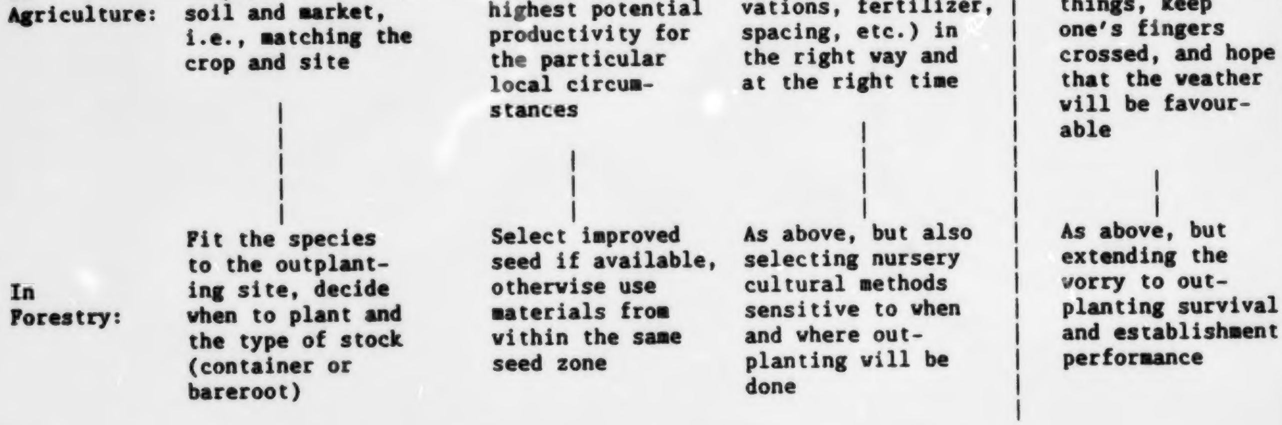
preparation and tending for plantation establishment. This contrasts with traditional nursery or field crop practice where the product (grain, fruit, flowers, vegetables) is either immediately consumed or considered to be ephemeral. Thus, the quality of most agricultural products is considered over a relatively short period (weeks or months) until harvest or sale (Hanan and Heins 1982). However, in forestry the influence of nursery characteristics are considered to persist for 1 to several years until establishment or the "free-to-grow" stage (Wood and Dominy 1985) or even much longer (Nienstadt 1981).

Thus, the environment in which crops are grown is far more complex in forestry than in agriculture (Fig. 1). Crops are grown according to very demanding end-use criteria, in a suboptimal climate, using less well-developed varieties in a cultural system with many technical and economic unknowns.

Nursery Economics

It takes money to fight climate. At first glance it seems strange that comparatively little effort has gone into surmounting the climatic restrictions imposed on a crop grown in climatically suboptimal regions, and where stock quality must be tailored for optimal performance over a time span measured in years. Yet, this is the case.

Production of seedlings is the first step in a complicated process leading to a forest product like lumber or paper. The remoteness of the nursery product from the end products makes it difficult for the industry to successfully answer the question, "How valuable are our seedlings?" This is **not** the same as asking, "What do they cost to produce?" The result is a reluctance to adopt expensive high-technology, high-cultural control options for reforestation stock because seedlings are not usually identified as a commodity. By contrast, the investment in an agricultural crop can be directly calculated based on the purchase price the market is willing to bear to receive a product of specified quality. Therefore, within the forestry context it also can be argued that economic unknowns, in addition to climate, are primary limiting factors.



Basis of crop productivity

	Policy	Plant	Techniques	Weather
In Agriculture:	Choose the right crop for the site, soil and market, i.e., matching the crop and site	Select the variety with the highest potential productivity for the particular local circumstances	Carry out the right operations (cultivations, fertilizer, spacing, etc.) in the right way and at the right time	Finally, having done all these things, keep one's fingers crossed, and hope that the weather will be favourable
In Forestry:	Fit the species to the outplanting site, decide when to plant and the type of stock (container or bareroot)	Select improved seed if available, otherwise use materials from within the same seed zone	As above, but also selecting nursery cultural methods sensitive to when and where outplanting will be done	As above, but extending the worry to outplanting survival and establishment performance

FIG. 1. Major determinants of crop productivity (adapted and expanded from Hudson 1975).

Although climate can severely restrict the success of nursery production of seedlings, the risk of crop failure does not appear to be a priority in determining the investment in cultural technology. Consequently, yearly climatic variation significantly compounds cultural difficulties in forest nurseries, as is seen by examining major problems reported by nurseries across Canada in 1986. Bareroot nurseries in Newfoundland and Nova Scotia had problems meeting shipping targets because of adverse climate. The cold, wet summer in Quebec and Atlantic Canada caused a loss of cultural control of growth, so that container crops showed excess height and the associated root and shoot diseases. Bareroot crops in a New Brunswick nursery suffered severe winter desiccation because there was no snow in January. Twenty-five million container seedlings were lost in British Columbia because of overwintering injury, although it is suspected that some of the injury is attributable to suboptimal cultural practices (E. van Eerden,[1] pers. comm. 1986). Overwintering losses of 4–6 million seedlings were recorded in Ontario, principally because of root freezing and disease damage (S.J. Colombo,[2] pers. comm. 1986). To minimize cultural costs to an acceptable level, nursery managers make compromises. There is an inevitable cost when cultural control is diminished because as Hudson has noted (also see Fig. 2) " . . . productivity depends only partly on good management, and more than we would like to admit on good luck." At growing costs of $150 per thousand, a loss of 30 million seedlings costs $4.5 million. In most cases, if a suitable capital investment had been made beforehand, luck could have been replaced by cultural control, thus avoiding the problem. However, decisions on the appropriateness of additional investments that increase nursery rearing costs are often made arbitrarily, using intuition and past experience rather than standard financial methods.

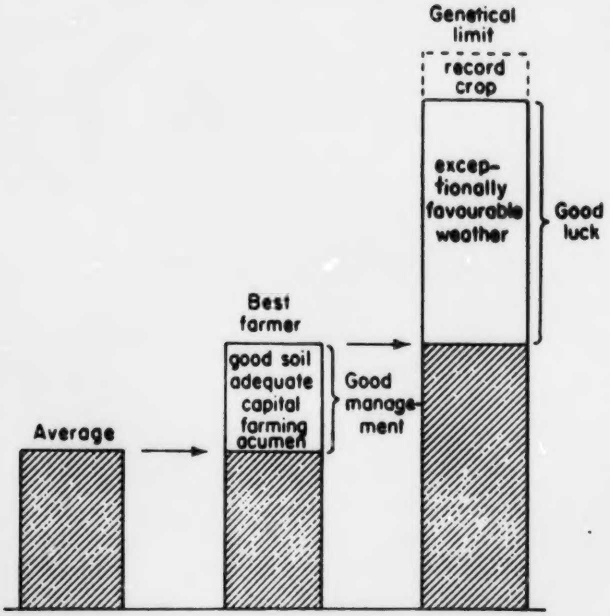

Genetical limit
record crop
excep-tionally favourable weather
Good luck
Best farmer
good soil adequate capital farming acumen
Good manage-ment
Average

FIG. 2. Increases in crop yield attributable to good management and to good luck (Hudson 1975).

There is little information on crop value (Kinghorn 1982, Hallett 1986), although alternative production costs can usually be estimated (e.g., Cameron 1982, Mattson 1982). Economic investments are difficult to calculate at the nursery site alone because seedlings are not yet considered a commodity, although a steadily increasing amount of contract growing may be helpful in determining future crop value. However, maintenance/enhancement of the forest resource will likely necessitate government control thereby complicating the assignment of marketplace values.

The question is therefore, "How are the benefits of good cultural practices to be estimated?" To assess the value of a forest nursery crop the postplanting performance of the seedlings can be considered. The criteria used are the percentage of planted stock that survives and the rapidity with which the seedlings overcome transplanting shock and become established in a "free to grow" condition. Two alternatives are obvious if planting is required to maintain the wood supply. Both use the predicted impact of various nursery practices on wood volume at harvest by predicting the percent field survival and different growth lag-times (the time interval between planting and seedling establishment) resulting from different cultural alternatives (Fig. 3). In regions where the price of wood is stable, the future values of differences in yield at harvest can be calculated. Current costs of a crop of seedlings raised in alternative ways can then be compared with future benefits. Assumptions about future economic conditions and the long-term business environment are required for this type of analysis (Timmis 1985). In other regions where a stable wood supply is a priority, site regeneration may be required by law (as in New Brunswick under the Crown Lands and Forest Act). If restoring a site to a defined level of productivity is the goal, then minimizing the total establishment cost required to produce the necessary volume at a defined harvest age becomes the objective. This cost depends on the total number of hectares planted and per hectare costs of planting stock, site preparation, planting, and tending. Total establishment costs plotted as a function of nursery costs then can be minimized (Fig. 4). This method has the advantage that no future value economic calculations are needed, but good biological data are required.

Future analyses of crop value will also include a value-added component from genetic improvements derived from tree improvement (TI) programs (Fig. 4). The economics of TI programs are based on the percentage gain applicable to wood production at interest rates forecasted many years into the future (Timmis 1985, Cornelius and Morgenstern 1986). Many of the techniques developed for general nursery use — particularly measures like osmotic priming or fluid drilling applied where seed is scarce and valuable — are applicable. Nursery culture is a critical part of tree improvement since successful plantation establishment using improved seed is critically dependent not only on maximized germination of improved seed but also on crop vigor and preconditioning to ensure high survival and rapid transition to a free-to-grow state.

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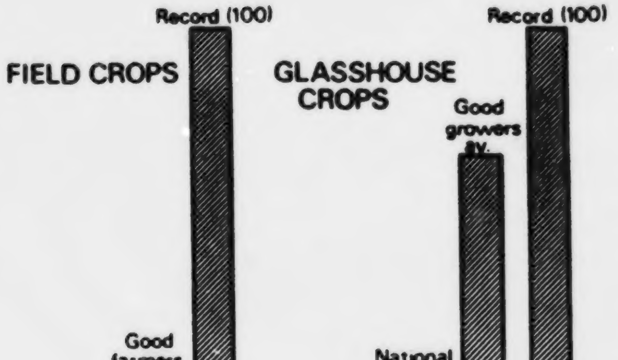

FIG. 3. Effects of partial control over the crop environment on the probable relation between average, "best grower," and record yields in the open and in greenhouses (Hudson 1975).

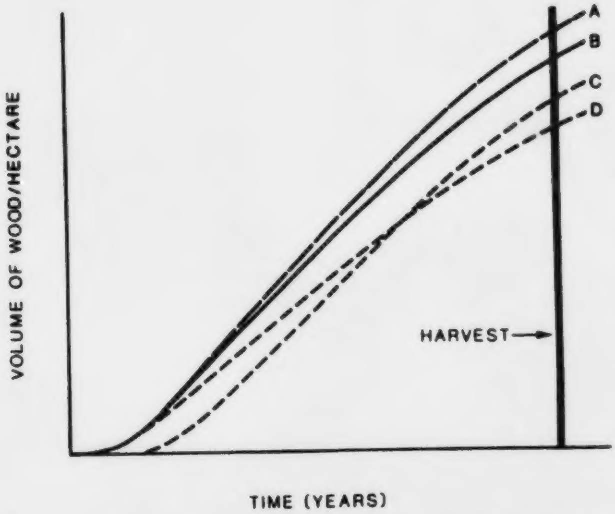

FIG. 4. Effects of nursery stock condition on volume yield at harvest. Curves show that either innovation/improvement in cultural practice or genetic gain increases volume (A) over mean values for the site (B). Poor quality seedlings produce lower yields because of either increased establishment time (C) or decreased survival (D).

Climate and Culture

Nursery techniques are altered in several ways to compensate for climate. These can be classified on the basis of terminology borrowed from the literature on plant environmental stress: avoidance or a passive approach, tolerance or compromise, and nonavoidance or confrontation (Levitt 1980).

Bareroot systems are a classic example of avoidance. A nursery site is chosen on the basis of local climate, soil and water quality, and the availability of other resources (utilities, labor etc.). For high-value agricultural sites such as orchards, sophisticated micrometeorological methods can be used in the selection process (Bartholic 1979). Fields are bedded and tiled if necessary to minimize erosion and washout from rainfall. They can also be aligned and planted with shelterbelts to minimize wind and promote the retention of snowcover for winter protection. Crops are managed strictly according to seasonal weather, with the goal of minimizing environmental stress. Growth is promoted through fertility and irrigation when conditions are good, and is monitored for dormancy and cold hardiness when they are not.

Some avoidance alternatives combine features of both bareroot and container cultures. Seedbeds are particularly sensitive to poor weather conditions. Drought, extended periods of wet and/or cold temperatures, winter desiccation, frost heaving, and competition from weeds all result in lack of germination or high germinant mortality. Plug, mini-, or accelerated transplant systems are used in lieu of a seedbed (Hallett 1984) to improve germination and establishment.

Examples of passive cultural schemes can also be found in the container nursery as well. Shelterhouses are commonly used for summer-grown crops. During the summer a shadecloth covering is used to reduce wind velocity and cut the ambient light intensity by 50% (Tinus and McDonald 1979). This provides cooling and relieves moisture stress. For overwinter storage, the same structure can be covered with white polyethylene and tightly sealed both to prevent desiccation and damp low temperature excursions (Duncan and McNiel 1982). Both summer and winter strategies moderate the prevailing climate.

Current nursery practice with container crops often extends the growing season into the spring and fall when there would be little or no active vegetative growth. Such methods represent a compromise between requirements for plants of specified size or form suitable for outplanting by a certain date and the cost of energy, or the need to grow large numbers of seedlings with limited greenhouse space (multiple cropping). The greenhouse is used to promote early germination (Tinus and McDonald 1979) or to extend growth into the fall (Colombo 1984). During these periods, limited environmental manipulation (heating, ventilation, short- or long-day photoperiodic treatment) is used.

The most aggressive nursery methods are used to grow crops out of season, directly confronting outdoor climate. In forestry, the double-layer polyethylene greenhouse operated during the latter part of the winter season (germination between January and March) currently represents the upper limit of cultural control. All major environmental parameters except for sunlight (heating, ventilation/cooling, humidity, CO_2, fertility, and irrigation) are monitored and controlled. The extent and sophistication of environmental regulation make direct expenses for energy and facilities high. However, in so doing, good crop management minimizes the chances of poor crop performance because of poor weather (the "good luck" factor). A similar philosophy applies in the frozen overwinter storage of seedlings. The crop is assumed to be of sufficient value to warrant packing in the fall into controlled cold storage in case erratic fluctuations in winter temperatures occur.

In the future, for selected crops — such as propagules of genetically improved material — that do not require a large growing area, even the limitations in the lighting and cooling capability of current greenhouses will be eliminated. A small phytotron (a collection of growth rooms and controlled temperature rooms managed as a unit associated with a greenhouse complex [Downs and Hellmers 1975]) is a logical development. In such a facility, the first stages of growth for high-value crops are completely isolated from the ambient weather and the environment can be completely controlled. The testing of commercial installations for production of ornamentals has already been reported (Traberg-Borup 1984), and small-scale micropropagation of conifers is practiced with this technique (Smith 1986).

Between each of the cultural levels outlined above, the amount of cultural control greatly increases while dependence on local weather decreases. This is the explicit expression of the belief that while optimal natural climate can grow good quality stock, total climatic control can outperform nature. A comparison between agricultural crops commercially grown either in the field or greenhouse bears out this supposition (Fig. 5, adapted from Hudson 1975). The deft use of environmental control can also screen for differences in growth between cultivars or clones (e.g., the speed of root development and mortality as a function of temperature [Smith 1986]).

There are several reasons, exclusive of economic arguments, why in forestry many different nursery systems and cultural methods are used to grow the same crops:

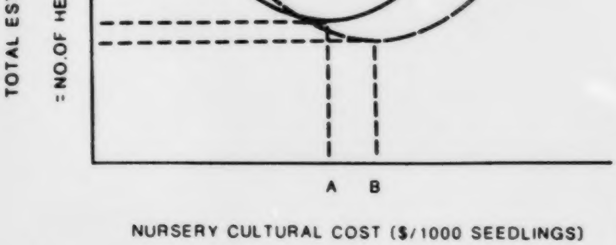

FIG. 5. Relation between total nursery cultural cost and total establishment cost (including nursery stock) without (A) and with (B) genetically improved seed. Dotted lines indicate preferred investment in stock culture to minimize total cost.

1. Climate can increase cropping time, shipping uncertainty, and the failure to meet planting targets. It can take from 1 yr in a nursery in a mild climate to 3 or 4 yr at a location with a harsh climate to grow a field crop suitable for planting. As the cropping time increases, it becomes more difficult to maintain predictable production levels, and erratic production impedes reforestation planning (Kinghorn 1982). A corollary to this is that as production time is reduced, the flexibility to deal with fluctuating stock demand, wasteful of both seedlings and site preparation, is increased (Tinus and Owston 1984).

2. There are differences in opinion concerning whether outplanting can be done almost continuously from spring until fall, or if narrower planting windows must be used. This consideration legitimately varies from region to region, with latitude, elevation, and species (compare Gardner 1982 with Mattice 1982.)

3. The importance of "natural" stock conditioning which can be provided only by outdoor weather is thought by some to have a positive influence on survival and vitality (Boyer and South 1984). This attitude originated because different cultural techniques produce seedlings with differing morphology (Burdett 1978, Thompson 1981), whose effects on outplanting success are unknown and therefore suspect.

4. Both within and between regions there are planting sites where bareroot stock performance is superior to that of container stock, and vice versa, even when the effects of handling and planting have been considered. This can be extended to within-stocktype comparisons (Hahn 1984, Hobbs 1984) and often reflects a lack of knowledge about matching stocktype to site environment (McMinn 1982).

5. Container culture is a relatively new technology. Many regions have a long history of bareroot culture. The confidence (and complacency) resulting from long-term experience with one set of methods breeds resistance to respond to new ideas (or fads) unless superior stock quality can be guaranteed. This rationale can be seen in nursery cultural trends in the mild climatic regions of the southern United States (Kinghorn 1982, Hallett 1986).

Although these arguments may be legitimately based on climatic differences, they are often equally based on anecdotal data, speculation, and intuition. Even if operational testing is done, the use of inappropriate field trials and/or comparisons coupled with inadequate documentation of environmental stresses at the planting site (Kinghorn 1982) can hamper decisions about which nursery culture alternatives to use.

Technical Considerations

Our understanding of environmental effects on crop physiology in forestry is rudimentary compared with knowledge about agricultural species. Even when a choice among several cultural alternatives can be made based on sound economics, implementation remains a problem because of a lack of technical knowledge. Historically, the evolution of both bareroot and container nursery practices has been biphasic. Improved cultural methods, by increasing cropping precision, generate better monitoring tools. As the knowledge of crop status increases, further improvements can be made to culture, and so on in a continuing iterative process. For example, there is a great deal of information on bareroot nursery soil fertility and growth, with accompanying recommendations for irrigation and fertilization. Significant cultural changes are unlikely until further information on internal effects useful for fine-tuning soil moisture and fertility levels are applied, such as the data of Brix (1981) indicating that net photosynthesis in current-year foliage of Douglas-fir decreases at foliar nitrogen levels above 1.6%, or the effect of maintained seedling moisture content on both seedling dry weight and shoot/root ratio (Barnette and Brissette 1986).

Monitoring emphasis varies according to the stage of nursery culture. The two delimiting cases are:

1. What is the crop status now? Examples in forest nursery management are a knowledge of the degree of seedling frost hardiness before moving a container crop outdoors in the fall or spring (Hallett 1984), and consideration of plant moisture stress in relation to lifting of bareroot stock (Day 1985).

2. What do the observations taken over a period of time indicate about the trend of crop growth, and will future scheduling be affected? Growth curves are an essential tool in crop scheduling (Tinus and McDonald 1979, Hallett 1982).

Morphological traits (dry weight, height, root collar diameter, etc.) are usually used for stock monitoring since they are easy to measure and morphology reflects the internal status, or physiology, of a plant and its interaction with the environment. The current trend in monitoring research is to emphasize the use of physiological indicators as management tools. There is general agreement that traditional morphological indices have become limiting. However, the experience in agriculture indicates that if various monitoring data can be analyzed as a whole (usually with a physiological/microclimatic basis), then interpretation using the more easily measured morphological traits can be enhanced through simple empirical relationships with climate (e.g., Charles-Edwards 1982).

As increasingly radical forms of cultural control are implemented, the ad hoc use of monitoring techniques in isolation becomes less effective. An integrated logical framework for analyzing the monitoring data, sometimes called a model, becomes necessary. Such models — and there can be several based on various stages of the cultural cycle — are useful in a variety of ways:

1. A model can show relationships between measured values which at first glance do not seem to be connected, and whose correlation can adapt or eliminate monitoring techniques to either increase the precision of and/or minimize the amount of monitoring necessary (e.g., the Degree Growth Stage model of Fuchigami et al. 1982).

2. Complex relationships between monitored variables can be synthesized within such a structure to yield a concise summary of current crop status. This is especially useful as the measurements become more physiological in nature (e.g., needle carbohydrate status (Puttonen 1986)) and therefore less easily related directly to traditional morphological benchmarks used by a nursery manager.

3. The predictive value of future crop development using simple models based on empirical observations is often excellent, even in bareroot culture where climate is not controlled (Bunting 1980).

4. Where intensive environmental control is practiced, the introduction of greenhouse climate computers offers for the first time an online capability using crop models to tailor stock growth based on sought-after crop attributes linked to climatic limitations. An interesting extension to this principle physically joins the plant to the monitoring system. Electrodes are used to provide an online "speaking plant" as one of the environmental modulators (Hashimoto et al. 1985). Algorithms are being concurrently developed for agricultural species that not only integrate climatic control with crop physiology, but also attempt to incorporate economic goals into the production targets (Challa and van de Vooren 1980).

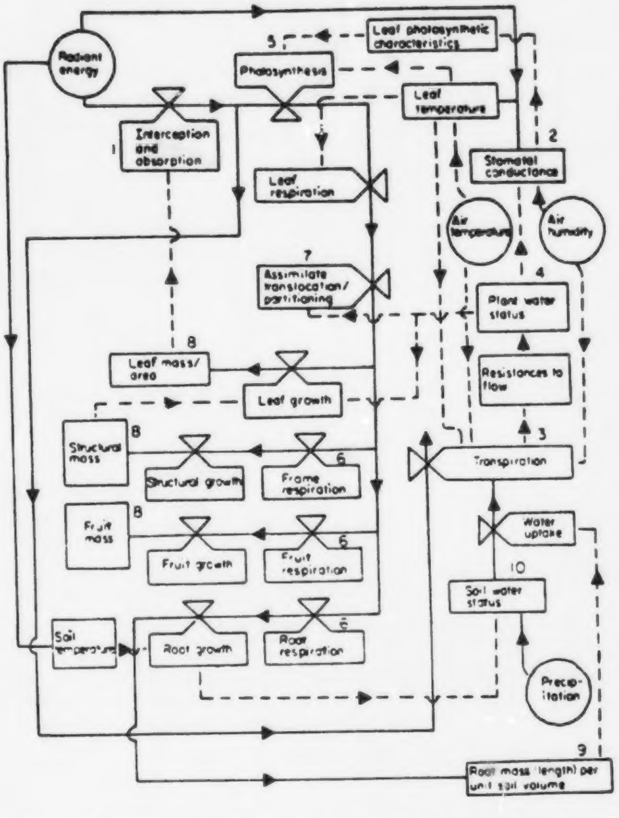
Radiant energy
Leaf photosynthetic characteristics
5
Photosynthesis
Leaf temperature
Interception and absorption
1
2
Stomatal conductance
Leaf respiration
Air temperature
Air humidity
7
Assimilate translocation/partitioning
4
Plant water status
8
Leaf mass/area
Leaf growth
Resistances to flow
3
Structural mass
8
Structural growth
6
Frame respiration
Transpiration
Fruit mass
8
Fruit growth
6
Fruit respiration
Water uptake
10
Soil water status
Soil temperature
Root growth
6
Root respiration
Precipitation
9
Root mass (length) per unit soil volume

FIG. 6. Schematic presentation of a model of plant growth in relation to weather. Solid lines represent flows of material; dotted lines are flows of environmental data. Valves (inverted triangles) represent rates; boxes are state variables; and circles enclose the environmental driving variables (Landsberg 1981).

For the purposes of modeling, most of the separate tools already exist (e.g., see Fig. 6, from Landsberg 1981), but need to be adapted and integrated. Computerized weather records or models based on regional climatic trends can be used for simulation of the environmental drivers (e.g., Degelman 1974, Cameron 1982). Crop models are becoming common in agriculture and may be chosen from a variety of types based on the intensity of management required (Jones 1986, Sands 1986). Similarly, greenhouse climate/growth models that also use outside climatic variables (temperature, daylength, light intensity, humidity, etc.) are being developed (Krug 1985a,b) though development still lags behind that for field crops (Challa 1985). Crop management models require an economic component. However, it appears that the integration of an associated economic analysis to build a "bio-economic model" for production is currently the least-developed system component (Liebig and Lederle 1985).

Conclusions

Crop environment and climatic influences on plant growth and cost are the driving forces behind the application of nursery technology. The preceding discussion indicates that forest nursery managers are required to make decisions about cultural alternatives even though there often is insufficient information to adequately do so. What we seek is the best compromise between stock quality and silviculture costs. Assessment is complicated because of both biological and economic unknowns and the solutions are interdependent. Methods that are unduly biased toward minimizing crop cost may mistakenly preclude cultural options which in reality have a good cost/ benefit ratio. Conversely, the expense of fine-tuning seedling biology at the nursery may not be recoverable in terms of improvements in postplanting performance.

Our technology will continue to increase the capabilities of cultural methods both to cooperate precisely with local climate and to innovatively circumvent it. Although an emphasis on the physiological level of research is currently appropriate, the optimal use of morphology and physiology as monitoring tools depends on the synthesis (models) of the two. There is much of value that can be learned from similar areas in agriculture.

Climatic effects on stock production and postplanting success ensure that both bareroot and container production methods will continue to coexist since there is a common goal — the production of biologically and economically viable plantations (Kinghorn 1982). The choices and fine-tuning of the methods will increasingly depend on the integration of climate, biology, technology, and cost.

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Temperature Influences on Reproductive Processes in Conifers

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Abstract

Temperature influences on floral initiation, sex expression, and pollen and seed development in conifers are reviewed, with special emphasis on its control to maximize production efficiency in containerized orchards. Many aspects of temperature are still unclear, but some generalizations are possible. Firstly, species vary in their optimal temperature regimes. Secondly, heat treatment is highly effective in promoting flowering in many though not all conifers, but its timing in relation to stage of reproductive bud development is critical. Thirdly, for some conifers the optimal induction temperature and/or its timing differs for female and male flowering. Finally, high temperatures conducive to abundant flowering can be deleterious to the developing seed and pollen. It is necessary to better define, on a species basis, the optimal temperatures and how they vary with stage of reproductive bud development.

Résumé

L'auteur étudie l'influence de la température sur l'induction florale, l'expression sexuelle ainsi que sur le développement du pollen et des graines; il insiste sur le contrôle de la température pour accroître au maximum la productivité des vergers de plants en contenants. Bien des aspects de la température ne sont pas encore élucidés, mais il est possible de faire certaines généralisations. Premièrement, les espèces varient quant à leurs régimes de température optimale. Deuxièmement, le traitement à la chaleur stimule très efficacement la floraison chez beaucoup de conifères, mais pas chez tous; cependant, le facteur décisif c'est de bien choisir le moment du traitement en fonction du stade de développement du bourgeon reproducteur. Troisièmement, chez certains conifères, la température d'induction optimale ou le moment du traitement diffèrent pour les fleurs femelles et les fleurs mâles. Enfin, les hautes températures qui favorisent une abondante floraison peuvent nuire aux graines et au pollen qui sont en train de se développer. Il est nécessaire de mieux définir, en fonction de chaque espèce, quelles sont les températures optimales et comment elles varient selon le stade de développement du bourgeon reproducteur.

Introduction

There are numerous investigations into climatic-flowering relationships and relationships derived from the southward movement of seed orchards which indicate that warm summer temperatures are conducive to abundant cone production in many conifers (Owens and Blake 1985). But such studies do not clearly distinguish between heat and the drought or light effects that may be associated with high temperatures, or photoperiod effects in the case of latitudinal transfers. While the distinctions may seem academic regarding siting and management of conventional soil-based seed orchards, they are critically important in containerized orchards where temperature, soil, water, and photoperiod can be controlled to maximize flowering and subsequent seed and pollen development (Ross et al. 1986).

Only in recent years have growth regulator treatments and container culture techniques for inducing precocious flowering in conifers become sufficiently reliable (Ross and Pharis 1986) that greenhouse and growth chamber studies could be profitably undertaken. Although there have been relatively few such studies to date, involving but a limited number of species, their results are beginning to provide a better understanding of how temperature influences reproductive processes. This paper provides a brief review of these influences, their complexity, and how they can vary with species and stage of reproductive development.

Current Status of Knowledge

Floral Initiation

The spruces have been most intensively investigated for temperature influences on flowering. Studies in which branches or entire crowns of field-grown trees were enclosed in plastic tents to create a "greenhouse" effect (e.g., Chalupka and Giertych 1977, Ross et al. 1986) provided the first confirmation of climatic-relationship investigations (e.g., Olsen 1978) regarding the promotive effect of high midsummer temperatures. The beneficial effect of heat on flowering of Norway (*Picea abies* L.), Engelmann (*P. engelmannii* Perry), Sitka (*P. sitchensis* (Bong.) Carr.) and white spruce (*P. glauca* (Moench) Voss) has now been amply demonstrated in numerous greenhouse studies on potted trees (Olsen 1978; Tompsett and Fletcher 1979; Philipson 1983; Ross 1985, 1987). With or without the adjunct induction treatments of gibberellin A4/7 (GA4/7) and drought, potted trees are much more responsive than crowns of field-grown trees to the greenhouse effect (Chalupka and Giertych 1977, Ross et al. 1986). This had led to the suggestion (Philipson 1983) that one effect of high temperatures on potted trees is to depress root activity, thereby retarding the export of some root-synthesized substance that is inhibitory to flowering. However, I found in a recent and as yet unconfirmed experiment with potted white spruce grafts that whereas root initiation, elongation, and O_2 uptake were progressively depressed with increasing soil temperature from 6 to 29°C, there was no relationship between these measures of root activity and the flowering response. Preliminary indications were that warm roots + warm shoots are not more effective than warm shoots alone in promoting flowering in this species.

The importance of proper timing of the heat treatment in spruce has only recently become apparent. Working with potted Norway spruce grafts, Tompsett and Fletcher (1979) reported an increasing flowering response with increasing time in the polyhouse. Unfortunately, they failed to relate treatment timing to stage of shoot development. Ross (1985,

1987) has shown for Engelmann spruce that the heat treatment is promotive only if applied once the new shoots have completed at least 85–95% of their seasonal elongation growth, the time when apical determination of bud type (vegetative or reproductive) normally occurs (Owens and Blake 1985). The flowering response is significantly reduced if trees are moved into the polyhouse earlier, during rapid shoot elongation, regardless of subsequent duration of the heat treatment. Both in this species and in Sitka spruce (Tompsett and Fletcher 1979), the optimal timing of heat treatment appears to be slightly earlier for promotion of male than female flowering. This is probably because, although both sexes of cones appear to differentiate at the same stage of shoot development (Owens and Blake 1985), pollen cones tend to be borne of less vigorous shoots that complete their seasonal development earlier (Ross 1985).

The optimal times for heat and drought treatments differ significantly, at least in Engelmann spruce (Ross 1985, 1987). In contrast to heat, drought is promotive of flowering only during the early and rapid stages of shoot elongation, having an inhibitory effect if applied later when heat is most effective (Olsen 1978). See Ross (1985) for a discussion of the possible physiological basis for this differential timing effect.

Owing to the limitations of greenhouse experiments, the optimal induction temperature has yet to be defined for any of the spruces. Based on investigations of long-term climatic-flowering relationships, both Olsen (1978) and Dunberg (1979) concluded that a daytime temperature of 30°C was about optimal for Norway spruce. In this species (Olsen 1978), as in Engelmann and white spruce (Ross 1985, 1987, and unpublished data), movement of potted trees into a polyhouse heated to provide 30°C days and 20°C nights has resulted in profuse female and male flowering. Yet, equivalent or even better flowering was achieved with the latter species in a closed but unheated polyhouse where day/night temperatures averaged only 5–7°C. Temperatures much above 30°C appeared to be deleterious (Ross 1987, and unpublished data).

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) has not been as intensively investigated as the spruces, but it is also highly responsive to properly timed heat treatment (Pollard and Portlock 1981, Ross et al. 1986). The two species, however, differ in one important respect. Whereas the optimal timing of heat treatment for promotion of flowering in spruce is the late stage of slow shoot elongation, for western hemlock it is during early and rapid shoot elongation (Ross and Bower, unpublished data), which is also the optimal time for drought and GA4/7 treatments (Ross et al. 1981; Ross, Bower, and Woods, unpublished data). This is consistent with the fact that, unlike spruce, apical determination of bud type occurs relatively early during shoot development in western hemlock (Owens and Blake 1985). In one of the rare growth-chamber experiments on a conifer, Pollard and Portlock (1981) compared the flowering response in young western hemlock seedlings to temperatures ranging from 20 to 35°C, where plants received no GA4/7, the growth regulator alone and with drought. In response to GA4/7 + drought, the mean production of seed cones increased from 0 to 31, and that of pollen cones from 4 to 55, with increasing temperature from 20 to 30°C; severe defoliation and mortality occurred at 35°C. GA4/7 alone was less effective but the temperature response was similar. None of the untreated seedlings flowered at any temperature. Note that these results apply to young (3-yr-old) seedlings. Young grafts of sexually mature trees will flower in response to heat alone, though not as profusely as when GA4/7 and drought or root-pruning treatments are also given (Ross et al. 1986).

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is another important conifer of the Pacific Northwest, and one for which the role of temperature in flowering is only now being appreciated. Ebell (1967) reported increased female and male flowering for potted grafts in a glasshouse versus outdoors, but only in the presence of drought. I have confirmed this for male flowering in several unpublished trials. Female flowering, however, either was nonexistent or was significantly depressed in the polyhouse relative to potted grafts treated outdoors.

In these studies with potted Douglas-fir, trees were moved indoors at or shortly before vegetative bud burst (VBB) and remained there throughout the growing season. Several other studies (Lowry 1966, van Vredenburch and La Bastide 1969) have correlated abundant cone crops for Douglas-fir in nature with a warm, dry June and July (i.e., mid-to-late shoot elongation), but a moist, cool March (that is, onset of elongation). Yet, drought is known to promote flowering only if begun at or shortly following VBB (Ebell 1967). Thus, the requirement for a moist March may be more specifically for cool temperatures, with high temperatures becoming beneficial later.

Recent results (Ross, unpublished data) clarify the effects of heat treatment timing and show that it differs for female and male flowering in Douglas-fir. Potted 2-yr-old grafts were left outdoors or brought into a heated 15°C polyhouse from VBB through end of shoot elongation (early period), for a similar duration thereafter (late period), or for both the early and late periods. Trees in all treatments received stem injections of GA4/7 throughout the early period only. Grafts indoors for the late period produced twice as many seed cones (21 each) as the outdoor controls (10 each). Early heat (8 cones/graft) appeared to inhibit female flowering relative to outdoor controls, as did early + late heat (15 cones/graft) relative to late heat only. Production of pollen cones, in contrast, was significantly increased by both the early and late heat treatments (78 and 92 cones/graft vs. 10 each for outdoor controls), with an additive increase (162 cones/graft) from early + late heat.

For pines, the role of temperature in flowering is rather confusing. There is indirect evidence from the southward movement of provenances and seed orchards that warm summer temperatures also are conducive to abundant flowering in many species of pine (Sarvis 1970, Schmidtling 1984). Yet such results may be confounded by shortened photoperiods, which appear to be conducive to female flowering (Longman 1982).

Working with field-grown Scots pine (*Pinus sylvestris* L.), Chalupka (1981) reported significantly increased female and male flowering on lateral shoots that had been enclosed in polyethylene bags for 6 wk during midsummer.

In an unpublished 1985 report of the Finnish Tree Breeding Foundation, R. Hagqvist recommends a 1-mo heat treatment of potted Scots pine breeding orchard ramets in July when apical determination of bud type normally occurs.

Advanced-generation breeding of loblolly pine (*Pinus taeda* L.) in the southeast United States is now largely being done in indoor-potted orchards (Greenwood et al. 1979). Although initiation of seed-cone buds is equally good for potted grafts outdoors, male flowering is considerably better in the greenhouse. However, according to Greenwood (pers. comm.), temperatures within the air-conditioned greenhouse can be below ambient for much of the summer, so the enhanced male flowering may not be a response to heat.

This would be consistent with Longman's (1982) finding for lodgepole pine (*Pinus contorta* Dougl.). Working in the growth chamber, he found that production of pollen cones was significantly better at 8°C than 15°C, especially under long days favorable to male flowering. Female flowering, however, was slightly better at the higher temperature. It is noteworthy that heat treatment began upon completion of shoot elongation, which would coincide with the time when differentiation of seed cones normally occurs, but after differentiation of pollen cones (Owens and Blake 1985).

SEX EXPRESSION

As already mentioned, timing of the heat treatment can influence the ratio of seed and pollen cones initiated in spruce and Douglas-fir, and possibly other conifers as well. Sex expression may also be under direct temperature control in some species. In a comprehensive growth-chamber experiment on *Cryptomeria japonica,* Nagao and Sasaki (1981) demonstrated that the optimal induction temperature for males (25°C) was significantly higher than that for females (15°C). This was not apparent for *Chamaecyparis obtusa,* where the higher temperature resulted in both abundant female and male flowering (Nagao and Sasaki 1981).

There is as yet limited evidence for a role of temperature in sex expression in the Pinaceae. There is Longman's (1982) report for lodgepole pine that the optimal induction temperature is lower for male than female flowering, but as previously suggested, this may be a matter of treatment timing. In a review of their own and other European work on Norway spruce, Chalupka and Giertych (1977) note that heat treatment by tenting of field-grown trees consistently has preferentially promoted male flowering. Yet, this is not readily apparent in the results of greenhouse experiments, for either this or other Pinaceae conifers reviewed in the preceding section. The only conclusion possible at this time is that such experiments do not afford sufficient environmental control to establish whether female and male flowering have different temperature optima.

POLLEN AND SEED DEVELOPMENT

Other than the desirability of freeze protection, relatively little is known about the optimal temperature regimes for developing cones. This is a matter of some practical importance, especially with indoor-potted orchards where pollen and seed may experience above-normal temperatures throughout much of their development. Moreover, it is frequently desirable to temperature force early shedding of pollen, so that it is available for artificial pollination in advance of female receptivity. This is typically achieved by enclosing catkin-bearing branches of field-grown trees in plastic bags, or by moving male-flowering potted trees into an unheated or heated polyhouse in early spring.

Properly employed, either technique can provide up to about a 2-wk head start in the collection and processing of high quality pollen (Winton 1964, Ross et al. 1986). However, Owens and Blake (1985) stress that conifer pollen is sensitive to high temperatures, especially where heat forcing is attempted before meiosis and the tetrad stage of pollen development. To illustrate the problem I draw on some as yet unpublished results for white spruce.

Young, potted grafts that had been induced to flower the previous year by heat, drought, and/or GA4/7 treatments and then overwintered outdoors were moved as the reproductive buds were beginning to swell in spring into either an open, closed, or heated polyhouse. Through completion of pollen shedding and pollination, day/night temperatures in the open, closed and heated houses averaged 5 ± 4°C, 6 ± 3°C and 18 ± 2°C, respectively. The pollen harvested was reapplied to receptive female strobili on grafts in the same environment. Thereafter, half the grafts in both the open and closed houses had their environments switched, and all grafts in the heated house were moved into the open house.

Temperature effects on pollen maturation were dramatic. In the heated house 50% of the pollen cones matured after only 19 d, compared with 27 and 41 d in the closed and open house, respectively. However, there was a marked decrease in the per cone yield of pollen with increasing temperature, from 74 μL in the open house to 22 μL in the heated house. This was largely related to abnormal and incomplete development of pollen cones at the higher temperatures. Pollen viability also was adversely affected, based on 32% filled seed in the open house, compared with 7 and 4% filled seed in the closed and heated houses, respectively.

Seed cones also matured more rapidly in the heated than open house. But they were similarly sensitive to high temperatures, especially during the prepollination stage of development. Cones developed normally in the open house, attaining a final length of 59 mm and dry mass of 2.9 g and containing 176 total and 32 filled seed each. By contrast, cones from grafts that spent the prepollination period in the heated house were 27% shorter, 59% lighter, with 35 and 92% fewer total and filled seed, respectively. Cones that matured in the closed house were intermediate in all respects. Temperature treatments in this study began in early spring, at about the time when meiosis in microspore and megaspore mother cells would normally occur. Had treatments been delayed a week or so later until after these sensitive processes were completed, the developing pollen and seed could perhaps have tolerated the elevated temperatures, which were not high in relation to those that cones might normally experience.

Conclusions

Temperature clearly has a profound influence on reproduction processes in conifers, influences that can be profitably used in containerized orchards to accelerate the breeding and production of genetically improved tree seed. Heat treatment is highly effective in promoting flowering in many though not all conifers, but its timing in relation to stage of bud development is critical and may vary with species in relation to patterns of bud development. Optimal induction temperatures remain to be established for most species, and the relative importance of peak temperatures versus daily heat sums and of day versus night temperatures also needs to be addressed. There is evidence for some species, at least, that the optimal induction temperature differs for male and female flowering. Ross and Pharis (1987) have discussed the practical advantages, in terms of pollen and other management activities, of maintaining separate potted orchards for production of seed and pollen. The possibility that sex expression may be under temperature control warrants further investigation, especially in conjunction with crown training and growth regulator treatments which may also prove useful in shifting the sex ratio (Ross and Pharis 1987).

Most of the research to date concerned temperature influences on floral initiation, so that relatively little is known about its effects on cone development following anthesis. The benefits of frost protection notwithstanding, subjecting trees to elevated temperatures in early spring, before the onset of meiosis in the microspore and megaspore mother cells, can adversely affect subsequent pollen and seed development. The practical use of heat to force early shedding of pollen (for use in artificial pollination) in advance of female receptivity requires further knowledge of the critical parameters of treatment timing and intensity, again on a species basis.

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Climate and Irrigation Scheduling in a Seed Orchard Environment

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Abstract

Seed orchards will be abstract as a viable continuous source of high quality seed only after the stresses imposed by the environment are understood and appropriate management practices are introduced. One of these environmental stresses is limited (and excess) water supply. The introduction of an irrigation system and scheduling program designed to minimize the length of time trees experience water stress during the growing season can alleviate this problem in seed orchard management. One of the most efficient methods of scheduling irrigation in a seed orchard is to use a weather-based program that considers the other factors (such as soil, crop, irrigation water, irrigation technology, and society).

This paper discusses the structure of the developed irrigation scheduling program and its implementation at the Goodie Lake North seed orchard near Sioux Lookout in northwestern Ontario. In addition, the results of the first two operational years will be presented.

Résumé

Les vergers à graines ne seront considérés comme une source viable permanente de semences de haute qualité que lorsqu'on aura une bonne compréhension des stress imposés par l'environnement et qu'on utilisera les méthodes de gestion appropriées. L'une des contraintes environnementales est l'approvisionnement limité ou excessif en eau. L'établissement d'un réseau et d'un calendrier d'irrigation conçus pour minimiser la période au cours de laquelle les arbres subissent une contrainte par l'eau pendant la saison de croissance permet d'atténuer ce problème de gestion des vergers à graines. L'une des méthodes les plus efficaces pour établir un calendrier d'irrigation dans un verger à graines consiste à utiliser un programme basé sur la météorologie qui tient compte d'autres facteurs (comme le sol, les plants, l'eau d'irrigation, la technologie d'irrigation et la société).

Cet exposé examine la structure d'un programme d'établissement du calendrier et de sa mise en application dans un verger situé au nord du lac Goodie près de Sioux Lookout, dans le nord-ouest de l'Ontario. De plus, on présente les résultats des deux premières années d'exploitation.

Introduction

To remain viable the forestry industry sector must have an accessible and continuous supply of high quality timber. One of the steps being taken by government and forest companies to ensure this future wood supply is the establishment of seedling seed production orchards. The objective of these orchards is to produce bountiful quantities of genetically superior seed. However, the potential seed productivity of these orchards (quantity and quality) is influenced by a series of environmental as well as genetic factors. One of the most important environmental factors is moisture stress which in seed orchard management can be both a desirable and undesirable phenomenon.

In terms of orchard establishment, availability of sufficient soil moisture is necessary to ensure the survival and health of the trees. However, once the trees have reached the seed producing age some degree of moisture stress is desirable to increase seed productivity. On the other hand, should this moisture stress continue beyond or occur after the differentiation of bud initials, flower productivity could be severely limited. The deployment of an irrigation system with a soil moisture status monitoring capability would reduce the probability of the orchard experiencing moisture stress during the establishment phase and provide the capability of managing moisture stress within these orchards.

The objective of this presentation is to describe the development of a method of monitoring soil moisture status within a seed orchard environment. This methodology was developed in response to a request by the Ontario Ministry of Natural Resources for assistance in scheduling the application of irrigation water in the black spruce seed orchards of northwestern Ontario. The development site is the Goodie Lake North seed orchard near Sioux Lookout in northwestern Ontario. This is an orchard of 5.2 ha planted in 1982 with 16 000 black spruce seedlings.

The adopted methodology uses existing technology and can be easily integrated into orchard management plans and practices. In this case, the relative distance of the seed orchard from the management unit's office must be considered when developing the operational aspects of the scheduling model. In addition, the need to produce operationally realistic and achievable estimates of irrigation requirements was a priority.

A climate-based model for determining the moisture stress of a given plot of land, whether under management for forestry or agricultural purposes, is both efficient and cost effective in terms of the human and financial resources required. It is neither labor intensive nor does it impact significantly on the type of management options available to the orchard manager (e.g., planting design, fertilization, weed control, harvesting). In addition, the resulting climatic data base and resulting climate/weather sensitivity can be exploited for other management practices such as more effective timing of the application of fertilzers, herbicides and pesticides, and the understanding of productivity variability and capability.

Most irrigation scheduling techniques have as their basis a water budget. This can best be expressed by the formula:

$$SMS_i = SMS_{i-1} + (R_{eff} + Irr) - (E_t + D)$$

where SMS is the soil moisture status on day i, R_{eff} is the effective rainfall (rainfall minus interception and runoff), Irr is the irrigation water added, E_t is the actual evapotranspiration, and D is the water loss due to deep drain. To effectively manage the soil moisture, the land manager must be able to solve this equation. The methodology adopted for the seed orchards in northwestern Ontario uses as its basis the technique developed by Spittlehouse and Black (1981). The fact that the original development of this soil moisture stress monitor was developed for a forested environment (Douglas-fir) in Canada was a primary factor in making the selection. Blind application of methodologies developed for non-forested environments and other climates (e.g., semi-acid and/or acid) can lead to unrealistic results.

The basis of the adopted methodology is a water balance equation similar to that above which provides daily estimates of the volumetric water content of the root zone. The weather data required to run the model are daily values of maximum and minimum temperature and relative humidity, solar radiation, and total rainfall. In addition to these parameters, site descriptors of slope, aspect, latitude, root zone depth, soil water retention, and drainage characteristics, an estimate of leaf area index, coefficients for evapotranspiration and interception relationships, and the value of the soil moisture status at the start of the irrigation season are required.

The evapotranspiration is calculated as the lesser of the atmospheric demand or the soil water supply limited rates. This type of approach is more realistic considering the limitation of available data (i.e., lack of physiological information) and the operational logistics of the seed orchard.

The atmospheric demand rate is calculated using the Priestly and Taylor approach which has the following form:

$$E_t = a\left(\frac{s}{s+g}\right)(R_n + G)/L$$

where a is a calibration factor (the ratio of the total energy available for latent and sensible heat fluxes), s is the slope of the saturation vapor pressure curve at the mean daily temperature, g is the physchrometric constant (0.066 kPa°C^{-1} at 20°C and 100 kPa), R_n is the net radiation flux density calculated from the solar radiation flux density (Spittlehouse and Black 1981), G is the soil heat flux density, and L is the latent heat of vaporization. The daily values of G are comparatively small compared with that of R_n and therefore are ignored in this model.

The calibration factor a typically has a value of 1.26 + 0.2 (Priestly and Taylor 1972) but its actual value is site dependent. The site-specific value depends on the relative magnitude of the energies available for latent and sensible heat flux and it has been suggested that this factor can be used to reflect the relative importance of advection in the evapotranspiration process. A value less than 1 would be used in the case of a site where advective suppression or strong surface control of E_t through the stomatal resistance of the leaves is dominant. On the other hand, a value greater than 1 would be used in the case where advective enhancement of E_t is dominant.

The soil limiting rate is incorporated into the model to reflect the fact that there is a maximum rate of water supply to the plant that the soil can maintain. It relates the evapotranspiration to the fraction of extractable water in the root zone. The relationship is expressed by

$$E_t = b\,(\mathrm{SMS}_{i-1} - \mathrm{Th}_{min})/(\mathrm{Th}_{max} - \mathrm{Th}_{min})$$

where b is an experimentally determined factor (Spittlehouse and Black 1981) characteristic of the particular site, Th_{min} and Th_{max} are, respectively, the values of SMS when transpiration virtually ceases and when the soil is at field capacity.

Drainage was calculated on a daily basis as a function of the current soil moisture status. Since the orchard was established on a site with deep, well-drained soils, drainage is a significant portion of the water balance. The expression used to estimate the daily drainage (Campbell 1974) was

$$\mathrm{DRA} = K_r\,(\mathrm{SMS}_i\,/0.3)^r$$

where R is a retention descriptor and K_r (125.0 mm day^{-1}) was experimentally determined from individual tests on soil samples of 0.3-m depth taken from the orchard.

Effective rainfall (R_{eff}) is the amount of water that enters the soil (i.e., that amount that is available to add to the soil moisture reserves) and considers the amount of rain that has fallen in a day and to a limited extent the rate at which it has fallen. This limited consideration of rainfall rate is a result of the 1-d time step used. R_{eff} is the algebraic sum of the recorded rainfall minus the portion of the rain intercepted by the vegetation and that portion lost from the plot due to runoff.

$$R_{eff} = R_{rec} - (R_{int} + \mathrm{RO})$$

where R_{rec} is the recorded daily rainfall, R_{int} is the intercepted rainfall and RO is the runoff and is a function of the amount of rain reaching the ground ($R_{rec} - R_{int}$).

Interception is calculated using the leaf area index (LAI) and assuming a maximum daily rainfall that appears to be entirely intercepted. This rainfall amount was experimentally determined for the site (0.2 LAI). Evaporative demands by the atmosphere were first met by the interception storage of the vegetative canopy.

In the case of runoff, if more than a specific amount (25.4 mm) has fallen within a day then it is assumed that some portion of that rainfall will be lost to the plot as a result of runoff. The actual amounts and characteristics of this loss will depend on the individual site's slope, soil type, and vegetative cover. An expression that estimates the quantity of water that could be lost to runoff is

$$\mathrm{RO} = R_{gnd} - [(R_{gnd}/25.4)^{\mathrm{kpc}})]\ 25.4$$

where R_{gnd} is the rainfall reaching the ground ($R_{rec} - R_{int}$) and kpc is an experimentally determined site characteristic parameter (0.75).

Methodology

These relationships provide the basic framework of the irrigation scheduling procedure. It was decided to adopt the basic procedure proposed by Spittlehouse and Black (1981) with some modification and to calibrate the various model parameters for the Goodie Lake North seed orchard. The calibration would be done over 2 yr and the ground truthing would be a weekly series of gravimetric samples taken throughout the "irrigation season" (June 5–15 through to September 10–15). These weekly gravimetric samples were taken at randomly selected locations throughout the orchard within the limits of the irrigation system.

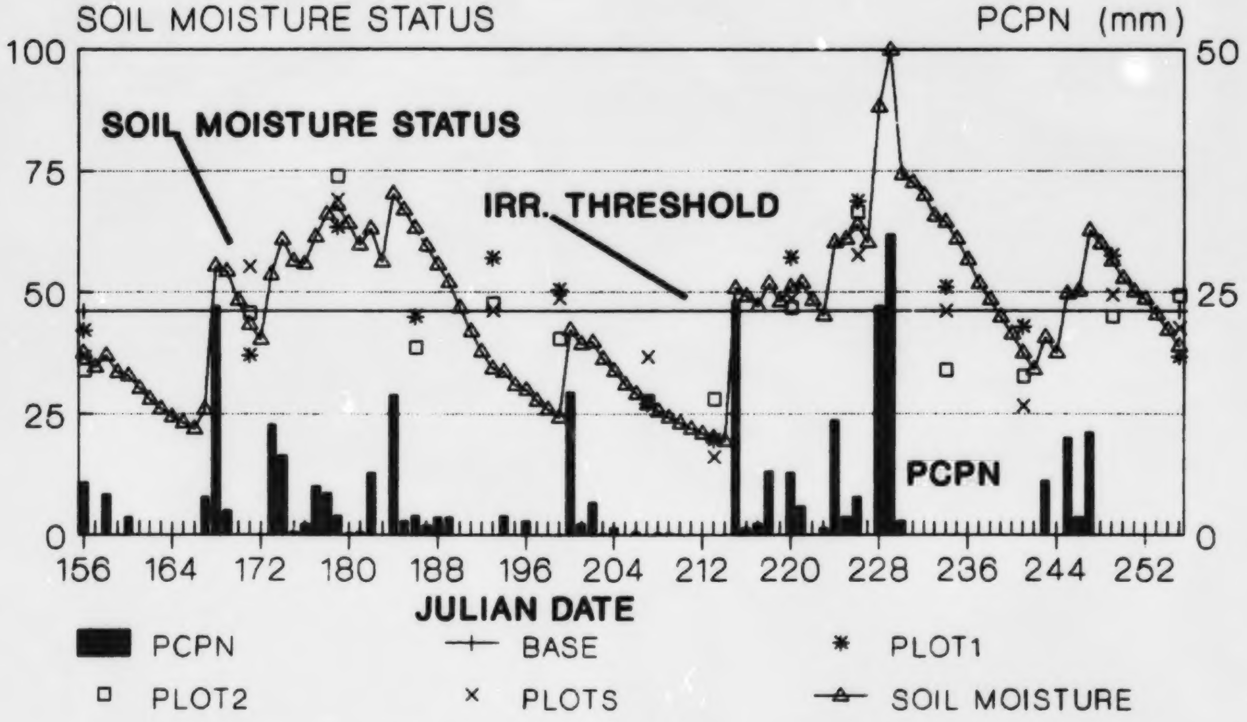

FIG. 1. Goodie Lake North, 1985.

In 1984 a basic climate station was erected on site to define the climatology of the seed orchard site. The station included an hygrothermograph and recording tipping bucket rain gauge. The following year a mechanical pyranograph was added to the site instrumentation and a previsionary irrigation scheduling model was implemented. This model was developed using calibration factors obtained through literature reviews and knowledge of site.

To define irrigation levels (i.e., when to turn on the irrigation system) it was proposed as a first approximation to use climatology to define two discrete levels below which it could be assumed that the trees would be experiencing stress. The selected values were based on the climatological "normal" soil moisture status during the previously defined "irrigation season" calculated using the available climatic data from Sioux Lookout. The two defined levels were the "average" and the "average" minus one-half a standard deviation. Using these values assumes that since black spruce is relatively successful in this area, the "average" climate of this area must meet the basic needs of the species. This type of approach is a good first estimate of the moisture stress levels; however, further experimentation is needed (e.g., growth statistics vs. soil moisture status) along with integration of physiological information for a better definition of moisture stress.

The results of the first modeled "irrigation season" indicated that refinement of the model and its calibration factors were necessary. The main deficiency in the first model appeared to be in the modeling of the drainage and in the *a* and *b* factors of the atmospheric demand and soil limiting evapotranspiration relationships, respectively. Refinement of the drainage model and the two *E*, factors improved the performance of the model. The results of the revised model are depicted for 1985 in Figure 1. The remaining differences between the gravimetric samples and the model's soil moisture status are not significant considering the operational nature of the irrigation system and model and the limitation of the gravimetric sample observations. The significant within-plot variations of the gravimetric samples are a result of the relatively uneven distribution of the rain and irrigation water (e.g., puddling) caused by micro-topographical differences, irrigation system leaks, and wind. However, they are also very real and have to be consided when designing any type of irrigation model particularly in a forested environment (seed orchard or nursery).

Discussion

These results show that a climate-based irrigation scheduling technique can operate within the functional limitations of a seed orchard and can give irrigation amounts that are realistically achievable. Using this type of system with properly defined species and site-specific moisture stress levels a manager can reduce the probability that trees within the seed orchard environment will experience moisture stress during the "irrigation season."

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Applications and Systems for Greenhouse Production of Trees

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Abstract

The production of containerized trees in greenhouses has become a standard technique for many species and in many regions. Applications of the accelerated-optimal-growth or protective culture concepts for trees include stock production for routine reforestation, for stress sites or other unique conditions, and for clonal propagation. Other applications are to conserve valuable seed, micropropagation of plantlings for nurseries, large seedling production, production of "difficult" species, seed orchard stock for outplanting, seed production in tall houses, and early genetic screening. Several systems for achieving successful protective culture are examined from both biological and logistical standpoints.

Résumé

La production d'arbres en récipient dans des serres est devenue une technique normalisée pour de nombreuses espèces et dans de nombreuses régions. L'application des concepts de croissance optimale accélérée ou de culture de protection pour les arbres comprend la production de matériel de reproduction pour la création courante de forêts, les terrains sujets aux contraintes, les endroits où prévalent des conditions uniques, ainsi que la propagation clonale. D'autres applications comprennent la conservation de semences de valeur; la micropropagation de jeunes plants pour les pépinières; la production de semis de grande taille, d'espèces «difficiles», de matériel de vergers à graines pour la création de forêts pérennes, de semences dans des serres hautes; et la préévaluation génétique. On examine du point de vue biologique et logistique plusieurs systèmes conçus pour réussir la production d'une culture de protection.

Introduction

The production of containerized tree seedlings in greenhouses has become a standard technique for many species throughout Canada, the United States, and northern Europe. The technique has grown steadily since its inception in the late 1950s but has complemented rather than supplemented bareroot nursery production systems in most regions. In fact, containerized tree production has stabilized

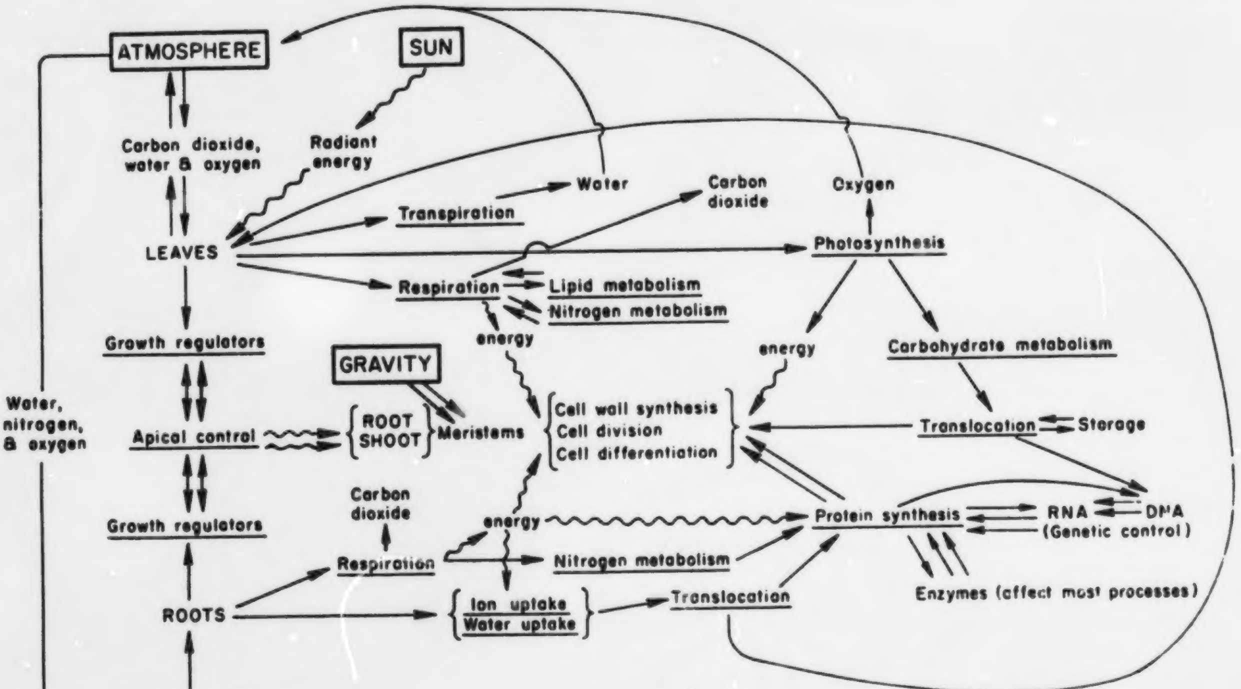
ATMOSPHERE
SUN
Carbon dioxide, water & oxygen
Radiant energy
Water
Carbon dioxide
Oxygen
Transpiration
LEAVES
Photosynthesis
Respiration
Lipid metabolism
Nitrogen metabolism
energy
energy
Carbohydrate metabolism
Growth regulators
GRAVITY
Water, nitrogen, & oxygen
Apical control
ROOT
SHOOT
Meristems
Cell wall synthesis
Cell division
Cell differentiation
Translocation
Storage
DNA
Carbon dioxide
Growth regulators
energy
Protein synthesis
RNA
(Genetic control)
Respiration
Nitrogen metabolism
ROOTS
Ion uptake
Water uptake
Translocation
Enzymes (affect most processes)
Water, minerals, other chemicals & microorganisms
SOIL
Flow of matter or process location
Control factor
Flow of energy

FIG. 1. Conceptual diagram of the interrelationships between environmental factors (*boxes*) and physiological processes (*underlined*) on tree growth and development.

or even declined in some regions such as the Pacific Northwest after a period of vigorous growth in the 1970s (Anonymous 1985). The primary advantages and disadvantages of greenhouse seedling production have been amply covered elsewhere (Tinus 1976, Hanover et al. 1976). My discussion will be restricted to defining the major applications for the protective culture of trees and illustrating some biological and logistical considerations common to most applications. My purpose is to focus on the biological potentials of climatic control of tree growth which may lead to a resurgence in the application of protective culture in forestry.

Applications of Protective Tree Culture

I first began growing trees in the greenhouse in 1958 to produce a large number of grafted blister rust resistant western white pines to establish a seed orchard in Idaho (Hanover 1962). Since that time I have seen a wide application of the general concept for both research and commercial purposes, and I predict that we will see a steadily increasing diversity and intensity of greenhouse tree culture in the future as our knowledge about how to do it, both biologically and economically, increases.

In regulating the climate in which trees are grown we are, in fact, controlling an array of chemical systems within the tree. These internal chemical systems are composed of substances involved in primary, central, and secondary metabolism, and growth-regulating compounds. Changes in concentrations and distributions of chemicals, in turn, regulate the morphology and physiology of the developing tree. In Figure 1, I have attempted to show diagrammatically how environmental factors we can control interact with physiological and biochemical processes to alter development.

The diagram only begins to illustrate the underlying complexity of our objectives in controlling tree growth. Our knowledge of the biochemical basis for growth control and how we may modify tree growth with chemicals is particularly meager (Hanover 1980).

Accelerated Optimal Growth (AOG)

Early in my work on accelerated growth of trees I realized that for many species, achieving dramatic increases in height growth through use of controlled environments was easy. The problem was in programing growth and development in an orderly way so that the final product was significantly better, internally and externally, than a tree grown in an outdoor nursery. For this reason I inserted the extremely important word "optimal" between "accelerated" and "growth" to describe the concept of total coordinated control of tree growth and development. The AOG concept has been described in the literature and is now widely applied in research. However, there remains a long way to go in its application to commercial tree production with the emphasis on "optimal"!

The components of AOG are shown in Figure 2. I will refer to them later in discussing several systems for achieving AOG (Hanover and Dickmann 1982, Hanover et al. 1976).

Examples of AOG Uses

Following are some examples of specific applications of AOG systems for tree species:

a) planting stock production

1. Mass production of tree seedlings for routine reforestation. The large-scale production of trees in greenhouses is occurring all over the world for selected species and often compares favorably economically with outdoor nurseries even in regions like the southern United States (Shaw 1985).

2. Production of seedlings for stress site plantings, sites plantable only at certain times of the year, and other unusual conditions requiring stock out of synchrony with outdoor nurseries.

3. Large-scale production of rooted cuttings or tissue culture plantlings. This application is limited to only a few situations at this time such as black spruce in Ontario (Armson et al. 1980) and *Pinus radiate* in New Zealand (Aitken-Christie and Gleed 1984).

b) specialty uses

4. High value seed conservation. With the advent of genetically superior seed derived from seed orchards the value of some seed now approaches $500 per pound. Often the seed is also in short supply so valuable seed can generate plantable seedlings most efficiently through a greenhouse container facility. This trend should increase steadily as better seed becomes available.

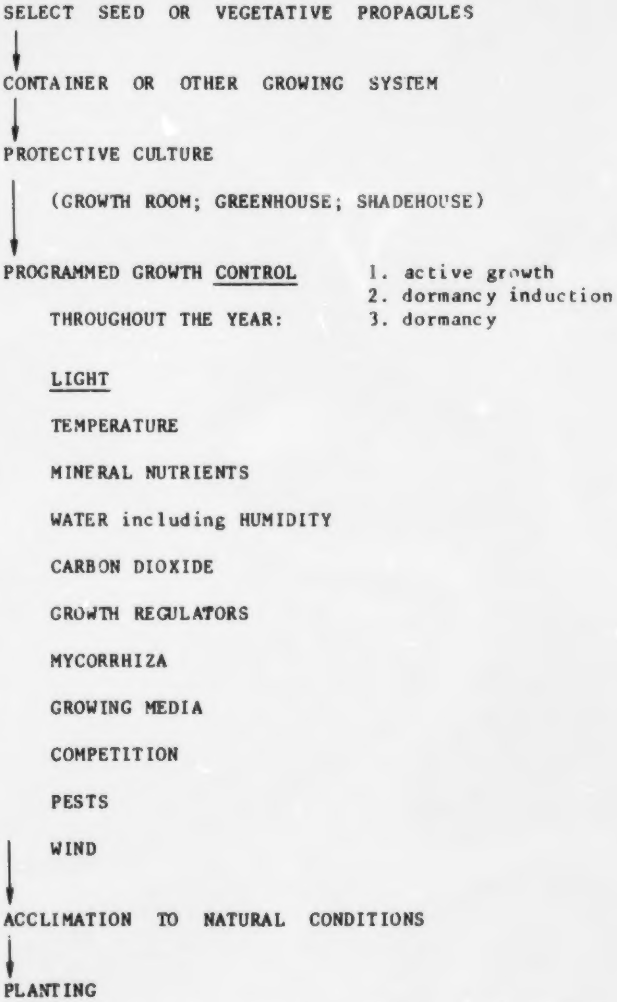

FIG. 2. Components of an accelerated-optimal-growth system to produce large, quality seedlings in **months** rather than **years**.

5. Micropropagation or tissue culture plantling production. Significant advances are being made in vegetative propagation, especially tissue culture, of both deciduous and coniferous trees. The opportunities for rapid utilization of genetically superior stock are greatly enhanced by clonal propagation. Planting stock derived from tissue culture plantlets, which I call plantlings to differentiate them from seedlings, must go through a greenhouse production system before transferring to the field. I foresee a major role for greenhouse culture of plantings in the near future.

6. "Difficult-to-grow" species. In Michigan we use AOG techniques to produce species that are very difficult to grow in outdoor nurseries. For example, we can produce excellent crops of *Abies* species in just over a year whereas 4-6 yr are required in the nursery. Other examples of species in this category are *Juniperus virginiana* and *Thuja occidentalis*.

7. Seed orchard stock. In Michigan, we have a large cooperative tree improvement program involving many species. Seedling orchards are established annually for the purpose of both commercial seed production and advanced generation breeding. All of our seed orchards are established using seedlings that are grown to a large size under AOG conditions. This procedure leads to rapid establishment, vigorous growth in the orchard, and early flowering (Young and Hanover 1976). The greenhouse culture system is a key component in this phase of practical tree improvement.

8. Production seed orchards. Some tree species are amenable to manipulation in controlled environments for the purpose of commercial seed production. The Finnish Foundation for Forest Tree Breeding has pioneered the use of tall greenhouses for seed orchards and breeding of birch (Anonymous 1976) and Norway spruce (Anonymous 1977). Others have also attempted to use large structures for orchards, but it is very expensive and probably best suited to research on controlled crossing to create high value breeding stock.

9. Early genetic testing and screening. Forest geneticists are very interested in evaluating genotypic performance of progenies as early as possible to be able to select and hybridize without waiting long periods of time. Accelerated growth techniques may be extremely useful in genetic testing provided the traits of interest are relatively unaffected by the environments simulated. Traits that are age or size related may also be expressed earlier as a result of growth acceleration (Bongarten and Hanover 1985). Finally, progenies may be transferred to field environments more quickly using AOG techniques allowing responses to be observed earlier (Hanover and Reicosky 1972). Thus, screening for such traits as disease resistance, drought tolerance, foliage color, wood characteristics, and many others is facilitated by protective culture techniques. However, extreme caution must be taken in carrying out and interpreting the results of these methods (Lambeth et al. 1982, Bongarten and Hanover 1985).

10. Large seedling production. There are several reasons why large (transplant size) seedlings may be grown in greenhouses. One would be to produce high value ornamental specimens, such as blue spruce, in a short period of time. Another reason is to cut a year or more off the rotation cycle for high value Christmas tree stock. Finally, large seedlings may be produced for planting on sites with minimum weed control or where deep roots are required.

There are undoubtedly other examples of the application of controlled environment methods in forestry, but those I described are some of the major ones.

Systems for Protective Tree Culture

There are as many or more different systems or techniques for growing trees in greenhouses as there are people in this room. My intention is not to review and summarize all the variations but to simply reflect on selected biological and mechanical considerations that I perceive may be useful or important in producing quality stock.

GENERAL CONSIDERATIONS

The primary consideration for anyone contemplating protective tree culture is a thorough knowledge of the growth physiology of a species. Literally untold numbers of catastrophes (small and large) have occurred over the years as a result of either lack of information on expected tree growth responses under controlled climate conditions or from neglecting to use information that does exist. For some species there are virtual "cookbooks" for growing trees indoors, but for many others we are still developing procedures. Species such as Douglas-fir, Scotch pine, larch, and most spruces are relatively easy to grow indoors while others such as white pine and red pine are difficult. Much more research is needed on the latter before AOG systems can fulfill their potential. For some difficult species new techniques, including chemical regulation, must be developed.

Because greenhouse grown stock usually is more intensively cultured than nursery stock it tends to be more costly. For this reason and also to maximize the quality of both seedling and the final harvested product, it is imperative that genetically improved seed be used whenever possible in most production systems. Unfortunately, we seem to be far from this goal due mainly to a shortage of improved seed in the market.

BIOLOGICAL CONSIDERATIONS

Several years ago we (Hanover and Dickman 1982) attempted to define in general terms the characteristics one should strive for to assure high quality planting stock. They include both morphological and physiological traits as listed:

"Good" genes, adapted to site environment
Dormant (and properly chilled for planting)
Well-developed terminal buds
High carbohydrate reserves
Optimum mineral status
Fully turgid (high water potential)
Large shoot, proper root/shoot ratio
Good stem caliper
High root-regenerating potential
Pest free
Mycorrhizae or nodules present
Uniform
Economical

Unfortunately, many greenhouse-grown trees fall considerably short of these key criteria. This is usually because an important factor of the environment is not properly used or controlled. I have selected a few factors for illustrative purposes.

Our research and that of others indicate that the terminal bud of a seedling is a veritable control center in terms of indicating growth or vigor status and potential for regrowth after outplanting (Young and Hanover 1978, Hanover 1980, Little 1980). Indeed, in many species the size of the bud is highly correlated with elongation potential in subsequent cycles. "Maturation" of the bud and satisfaction of its chilling or dormancy release requirement are factors important to further development of the whole seedling under controlled or natural environments (Heckmann 1985).

Leaves of trees grown under the still air, high humidity, and low light intensity of most greenhouses develop quite differently than those grown in outdoor nurseries. The most conspicuous difference is a complete lack of or poorly developed hypodermal. This layer of cells just beneath the epidermis serves as a protective tissue against radiation, wind desiccation, and abrasion. Protective culture seedlings usually have more succulent leaves, and stems as well, if not properly conditioned after the grand growth flush.

Most foresters are by now aware of the serious consequences of planting tree seedlings or larger trees whose roots have been "formed" by the container in which they are grown (Van Eerden and Kinghorn 1978). "Hip" roots, spiral roots, "J" roots, kinked roots, and thin roots are common abnormalities that affect tree growth and survival. These and many other root problems are easily avoided if proper precautions are taken. Container size and configuration, time in container, and environmental conditions applied during each phase of growth must all be optimized to control root as well as shoot growth in the greenhouse.

LOGISTICAL CONSIDERATIONS

With the multiplicity of applications for accelerated-optimal-growth of trees in mind, I would finally like to point out some logistical aspects of these applications. Again, due to time constraints I cannot be comprehensive, but I have chosen to illustrate major growing systems which may or may not be in present use.

There are two basic growing strategies in the production of greenhouse trees which profoundly affect both the biology and economics of accelerated growth systems. Simply stated, we can produce either small seedlings at a high density in a short period of time or larger seedlings at lower density over a longer period of time. To take full advantage of the AOG concept the second option is by far the choice. But this is where economics usually dictates use of the first option or a compromise between the two. Everything else being equal, larger seedlings are much preferred over small ones and indeed, except perhaps for very long rotations, the cost of producing large seedlings will be offset by greater survival, faster growth, and a shortened rotation. It may be possible with creative growing strategies to have the best of both worlds.

The range of sizes and configurations of containers available to growers reflects this dilemma. One can select a tiny container to produce a tiny tree which is very fragile when outplanted — hence, the movement by many growers to placing tiny greenhouse seedlings into transplant beds for a year or more. This procedure can result in very respectable seedlings for planting after 2 yr but at a cost that may be no different than conventional nursery systems.

Another advantageous growing strategy is to produce barefoot seedlings in the greenhouse. This can be done in at least two ways. Seed can be sown in prepared seedbeds on the greenhouse floor and seedlings can be harvested after reaching the right size and dormancy status. This technique certainly reduces container media and labor costs and can result in a very sturdy, vigorous seedling ready for outplanting. Of course, some flexibility is lost in terms of production scheduling and there is root disturbance, but the technique allows application of all other principles of AOG and deserves more scrutiny by growers.

TABLE 1. Two crop accelerated growth schedule for spruce seedlings with minimum energy input at East Lansing, Michigan.

Month	Greenhouse			Shade
Feb.	Sow crop — heat			
Mar.	Grow — heat			
Apr.	Grow — heat			
May	Grow — light		15th:	Sow crop
June	Grow — light			Grow — no light
July	Grow — light	Move	Move	Grow — no light
Aug. 15th	Grow — light		15th:	Plant or harden
Sept.	Grow — light + heat			Harden
Oct.	Grow — light + heat			Harden
Nov. 15th	Budset — no light; heat		15th:	Dormant — storage
Dec.	Budset — no light; low heat			Dormant — storage
Jan.	Harden — no light	Move		Dormant — storage
Feb. 15th	Begin new cycle			Dormant — storage

A variation on the "in ground" method is one employing multiple tree containers (noncompartmented). Here seeds are sown in large containers in the greenhouse. Each container may have 10 or more seedlings which are grown to size, hardened, then bare rooted. We have produced excellent crops of spruce and other species using this technique. The main advantage is it allows good root systems to develop and minimal root damage upon "lifting" or "depotting" (Hanover and Reicosky 1972).

Another variation on the multiple tree container method is to grow in very large containers, actually in raised benches similar to those used widely by the horticulture industry to produce rooted cuttings of woody plants. This may be the system of choice in producing vegetative propagules either by cuttings or by tissue culture plantlets.

If greenhouse seedlings are grown in containers, as most are today, there is another option for the flow of material in addition to moving from greenhouse to plantation or transplant beds. To make the most efficient use of a greenhouse and particularly extended photoperiod and heat assumption, a cycling scheme similar to one shown in Table 1 can be used. This system is based on the fact that many species do not need long days for accelerated growth during the 1-3 mo after germination. Therefore, seedlings can be cycled in and out depending on their stage of development.

No discussion of protective culture would be complete without mention of the kinds of growing structures that may be used. These structures vary from almost completely automated glasshouse facilities costing millions of dollars to very inexpensive double layer polyethylene Quonset-type houses. AOG in its various forms can be accomplished in just about any structure as long as the environmental factors

TABLE 2. Height growth of two species (cm) after 5 mo of AOG on a three-level growing facility located within a greenhouse.

Species	Lower level	Middle level	Upper level	Control[1]
Japanese larch	23.1a[2]	23.0a	16.6b	20.9a
Scotch pine	8.3a	7.3b	6.0c	8.1a

[1] Control was located on an open greenhouse bench.

[2] Mean values in a row and followed by same letter are not significant.

listed in Figure 1 can be controlled. Degree of control will vary, however, and certainly structures to be used for research purposes may require finer control than those used to mass produce seedlings for reforestation.

At Michigan State University we do both mass production and research, and our greenhouses reflect both economy and adequate environmental control. For example, for safety our greenhouse covering is rigid fiberglass and for fuel economy we cover it with one layer of air-inflated polyethylene. We grow both on the ground and in containers depending on species and objectives. We have also experimented successfully with a three-level growing frame within the greenhouse to increase production capability of containerized larch and Scotch pine (Table 2).

For seed orchards or other situations requiring higher ceilings, tall houses similar to those developed in Finland are appropriate. As stated earlier, the combinations of growing structures, cycling schedules, container or media types, degree of mechanization, economics, and overall objectives provide an enormous number of systems available for greenhouse production of trees. Combined with use of valuable new genetic materials and new technology developments, these systems provide powerful tools for high yield forest regeneration in the future.

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A Greenhouse Climate to Produce Container Seedlings for Post-Planting Survival and Growth

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Abstract

The objective of growing seedlings/rooted cuttings in the greenhouse is to ship healthy stock that will survive after out-planting. To achieve this objective a grower must first be informed of the future size of the seedlings and the container type required by the forester. The size of seedling and container type would depend on the planting site. Secondly, understanding how a plant grows is required to properly manipulate the greenhouse environment to achieve the targeted size and physiological state of the seedlings. With this knowledge a grower can supply all the necessary ingredients in the correct order and amounts to obtain the desired results. Some of the ingredients a grower should consider are light, carbon dioxide, oxygen, water, temperature, media, media amendments, pest control, and genetics.

The growth and development of a tree seedling are the product of a continuing series of chemical reactions. These chemical reactions must occur in proper sequence and/or simultaneously. There are many chemical reactions that occur in a tree seedling — some are known, of which very few are fully understood. The best known is probably photosynthesis — the absorption of light energy and its conversion into stable chemical potential.

It is outside the scope of this paper to address the effects of all the possible combinations of light, water, temperature, etc. on the growth of the tree seedling in the greenhouse. Only the effects of some of the major greenhouse environmental factors on certain aspects of tree seedling growth will be discussed.

Résumé

L'objectif de la culture en serre de semis et de boutures enracinées est l'expédition de plants sains qui survivront après l'établissement des plantations forestières. Pour pouvoir atteindre cet objectif, le planteur doit d'abord être informé de la taille future des semis ainsi que du type de récipient requis par le forestier. La taille des plants et le type de récipient dépendent de l'emplacement de la plantation. Ensuite, il faut bien comprendre comment croît une plante pour adapter l'environnement de la serre de façon à obtenir la taille et l'état physiologique cibles pour les semis. Avec cette information, le planteur peut fournir tous les éléments nécessaires dans l'ordre et en quantité appropriée pour obtenir les résultats désirés. Parmi les éléments que le planteur doit prendre en considération, mentionnons la lumière, le gaz carbonique, l'oxygène, l'eau, la température, les milieux, les fertilisants, la lutte contre les ravageurs et la génétique.

La croissance et le développement d'un semis d'arbre sont le produit d'une série continue de réactions chimiques. Ces dernières doivent survenir dans l'ordre approprié ou simultanément. De nombreuses réactions chimiques ont lieu dans un semis d'arbre, mais très peu parmi les quelques-unes qui sont connues sont parfaitement comprises. La mieux connue est probablement la photosynthèse, c'est-à-dire l'absorption de l'énergie lumineuse et sa conversion en potentiel chimique stable.

L'examen des effets de toutes les combinaisons possibles de la lumière, de l'eau, de la température, etc., sur la croissance des semis d'arbres en serre, dépasse le cadre du présent exposé. On ne traitera ici que des effets de quelques facteurs environnementaux majeurs de serre sur certains aspects de la croissance des semis d'arbres.

Introduction

Northern Clonal Forestry Centre (NCFC) produces 1 million rooted cuttings annually from full sib seedlings. The greenhouse complex was completed in November of 1984, at Moonbeam, Ontario, and is operated by the private sector, consisting of four shareholders — Rosaire Filion (President), Gaetan Filion (Manager), Aimé Filion (Vice-President), and Carmel Brulé (Director).

There are two crops of rooted cuttings produced per year. The current crop of 250 000 cuttings is started in January and ready for planting by mid-June. The overwintered crop of 750 000 cuttings is started in May and reaches shippable size by the end of August. This crop of rooted cuttings is overwintered and shipped the following spring.

The 37 000 donor trees that are started in November produce 250 000 cuttings in January and 750 000 cuttings in May before being discarded after the May cutting. Thirty thousand donors are selected from the best clones or "production clones" of rooted cuttings. The cuttings from these donors are used for conventional out-planting on the better sites. The other 7000 donors come from rooted cuttings that were taken from full sib seedlings germinated the year before. The new clones that make up the 7000 donors are tested for both greenhouse and field performance. After the tests are complete the new clones are compared with the older production clones by NCFC and Ministry of Natural Resources' Northern Forest Development Group (NFDG). The top clones from the new clones and old production clones are selected and become the following years' production clones.

Some Factors Affecting Seedling Growth

LIGHT

Light is the most important environmental factor that triggers various developmental steps in the seedling/cutting. The presence or absence of light is as important as the quality, quantity, and periodicity. The quality of light affects photosynthesis — both far-red light and blue light are required for photosynthesis to occur efficiently.

The quantity or intensity of light directly affects the rate of photosynthesis. As light intensity increases so does the rate of photosynthesis until the dark reaction in photosynthesis becomes limiting. This limit or light saturation point can be increased by increasing the carbon dioxide concentration. However, if light intensity greatly increases above the light saturation point it may be damaging — solarization is the photodestruction of chlorophyll by excessive illumination. Conversely, as light intensity decreases so does the rate of photosynthesis. Stomata, the little pores in the needles of the seedling that allow the exchange of gases (oxygen, carbon dioxide, and water), usually open in the light and close in the dark. Since photosynthesis cannot occur without the presence of carbon dioxide it is important that the stomata are open to allow gas exchange.

The length of light or photoperiod controls apical growth of the tree seedling. Photoperiod helps induce bud flush, growth, flowering, and dormancy. The process of frost hardening is complex and not well understood. However, it is closely tied with the effects of photoperiod in conjunction with a series of specific pretreatments to achieve maximum frost hardiness. By reducing the length of photoperiod it is possible to cause dormancy in a crop. It is desirable to handle, ship, and out-plant dormant, healthy rooted cuttings/seedlings, not actively growing stock, to reduce "planting shock" and increase survival in the field after out-planting.

Extended photoperiod in conjunction with high nitrogen feedings does accelerate the rate of top growth of seedlings and rooted cuttings but an excess of either may also increase the top root ratio.

WATER

After light, water has the greatest effect on the well-being of the seedling/rooted cutting. The rooted cutting requires water for many purposes. Water affects the trees in two forms — liquid and vapor. As a liquid it comes in contact with the crop as irrigation water or condensation. As a vapor, water comes in contact as relative humidity.

How water is controlled is a critical factor on the well-being of the crop. A grower can avoid many diseases from infesting a crop by closely monitoring the amount and timing of the irrigation. If a grower allows excessive or insufficient water to remain in the media for a prolonged period, damage to the roots will occur. This leads to reduced growth rates, disease, and a high top root ratio. A water shortage will cause the stomata to close even if all other factors are at optimum levels. If the stomata are closed, no photosynthesis can occur, hence no growth.

The quality of water is very important. If the water is contaminated with weed seeds, fungi spores, or pesticides, high pH levels, high or low pH disease problems, and/or abnormal growth will prevail. Therefore, it is important to test the irrigation water on a regular basis and adjust the irrigation water treatments to compensate for any abnormalities in the water. For example, a level of sodium (Na^+) in the irrigation water that does not harm the roots due to high salinity but is high enough to allow the seedling to absorb it can prevent the absorption of potassium (K^+). A potassium deficiency may result even though adequate levels are being applied by the fertilizer program.

MEDIA

The media supplies the physical support and some of the nutrients for the rooted cutting. Even the soilless mixes used in most greenhouses for the production of tree seedlings are not just containers of water and nutrient salts. The media-root relationship is a dynamic, living complex. The type of media selected must meet both the biological needs of the tree seedling and the practical needs of handling the containerized tree seedlings in the greenhouse and the field.

For the biological requirements of a tree, a media must have good texture for the tree seedlings. This refers to the size of the individual particles. The size of these particles determines the water holding capacity of the media. The media must also have good structure which refers to the organization of the media into aggregates. A large surface area is required to ensure good water holding properties and good aeration.

Organic matter is important for the maintenance of media structure and water holding capacity. Rooted cuttings produce many fibrous, supple roots in a peat-vermiculite media, whereas in a peat-sand media the root system usually consists of a few, large, thick, brittle roots. However, the structure of a peat-vermiculite media is very fragile and improper use of mixing and filling equipment can do irreparable damage by excessively compacting the media into the container and/or by crushing the vermiculite and reducing the peat fibers to dust. This may lead to a poorly aerated media with the associated disease and moisture problems.

Nutrients are continuously being added or removed in many ways; also, pH, oxygen content, microorganisms, and the ion exchange capacity of the media affect the amounts and availability of these nutrients. A peat-vermiculite media usually has a pH that is correct for a soilless media. Properly prepared peat-vermiculite media has more than sufficient aeration and a very high ion exchange capacity. Depending on the source of peat the microorganisms present in the peat are usually not harmful, but some peat bogs do appear to contain inhibitors that reduce the growth rate of the seedlings (Timmer and Folk 1986). There is evidence that this media also provides the best survival for out-planted seedlings (Phipps 1974).

NUTRIENTS

The major elements of the seedlings' organic structure are carbon, hydrogen, and oxygen. There are many other elements in various chemical forms. Calcium, magnesium, potassium, nitrogen, phosphorus, and sulfur are elements required in relatively large amounts by the seedling and are called macronutrients. The other elements such as iron, manganese, boron, copper, zinc, chlorine, and molybdenum are required in much smaller amounts and are referred to as micronutrients. It is noteworthy that problems with the growth of the seedling can occur not only because of the lack or absence of a particular element but also because of an excess of a particular element. For example, an excess of calcium may prevent or reduce the ability of the seedling to take up phosphorus. Most of the commercial conifer fertilizers more than adequately supply the seedlings with all the required nutrients in the correct proportions. The micronutrients serve as catalysts in the seedlings. The exact relationship of many of the micronutrients is not yet fully understood. It is known that a micronutrient can be toxic to seedlings if present in greater than trace amounts.

CONTAINER

The type of container can affect the performance of a seedling in the greenhouse and consequently the performance after out-planting. Selecting a proper container is similar to selecting a good media. Both the biological and the practical aspects must be considered.

Proper drainage is very important. A container with a high depth to width ratio drains much better than one with a low depth to width ratio. Sanitation is extremely important because contaminated containers cause disease. Therefore, ease of cleaning is important to remove all debris in the container from the previous crop. The material out of which the container is constructed can affect the growth of a rooted cutting. For example, if the container is made of a biodegradable material, then the growing population of bacteria that breaks down the container will compete with the rooted cutting for nitrogen (Timmer and Armstrong 1984). The volume and diameter of the container determine the size of the seedling. Therefore, if a large seedling is required for a particular site then a large container should be used with the corresponding added growing time. A seedling cannot be held indefinitely in a container. There is an optimum period of time in which a seedling can be grown in a given sized container after which the seedling deteriorates and dies. The container must be a size and weight that can be economically handled by the grower, shipper, and planter. Finally, the container must in no way be responsible for any post-planting mortality. The objective is to grow and plant seedlings/rooted cuttings to achieve survival and growth after out-planting.

TEMPERATURE

A seedling is the product of numerous chemical reactions. The rates of these chemical reactions depend on temperature. Respiration is not light dependent and can continue in the dark. Noting also that respiration is the process by which the seedling obtains energy to grow and develop, namely the oxidation of the organic compounds produced by photosynthesis, the correct selection of day-night temperatures is important to produce healthy, sturdy tree seedlings. For example, temperature influences cell length of the wood being formed by the seedling (Bidwell 1974). Usually, increased temperatures cause increased cell length, especially for night temperatures. High night temperatures tend to produce tall, spindly seedlings versus shorter, sturdy seedlings with low night temperatures. Very low night temperatures may cause Botrytis, dormancy, and short tree seedlings. Temperature also partially influences stomatal opening.

GENETICS

Black spruce has great genetic diversity. At NCFC it was noticed that there are greater differences within a family of clones than between families of clones. For example, a family that generally exhibits the best form may contain the clone with the worst form of all the families. The selection process is based on a clonal rather than on a family basis. The clones are both greenhouse and field tested to determine which clones will be used for the production of general reforestation stock.

Some of the clones identified as fast growers in the greenhouse were compared with medium and slow growers on the basis of drought tolerance. Rooted cuttings from fast growing clones did not have lower drought tolerance and may, depending on the clone, have increased drought tolerance (Blake and Ford 1986). There appears to be a direct correlation between the fast growth of fast growing clones and the higher photosynthetic rate of these clones compared with the slower growing clones.

Based on the previous years' greenhouse and field clonal testing, the poorer clones (that is, slow growth; exhibits plagiotropism, bad form, and poor field survival) were dropped. It is possible to select clones on the basis of fast growth, good form, planting survival, pest and disease resistance, site specificity, fiber length, and many other features. The more clones tested, the greater are the probabilities of achieving the desired feature in less time. NCFC and NFDG initiated an Early Testing of Clones Program. This will allow a much larger number of clones to be tested without proportionally increasing the square feet of greenhouse and increasing the number of clonal field trials. Initially the program will attempt to find a correlation between the early growth of the seedling and its rooted cuttings with field performance. Some of the tests would include the measurement of seed respiration rate, photosynthetic ability, frost hardiness, drought tolerance, growth hormone test (an application of gibberellic acid on good clones has no effect as opposed to an increase in growth on poor clones), rooting ability, growth, form, normal bud set, and normal bud flush. Some of these tests may be dropped and others added. Once a correlation has been established, only the clones that pass all of the tests will be field tested in clonal screening trials and be used for production of general reforestation stock.

Conclusion

Good clonal stock combined with sound cultural practices both in the greenhouse and the field will produce a stand of economical black spruce trees. We must constantly stay abreast of new developments and be willing to make changes in our cultural techniques to improve the growth of the seedlings/rooted cuttings both in the greenhouse and the field. We must be constantly upgrading the clonal stock to meet future needs.

It is most important that researchers, nursery people, and foresters see themselves as equal partners striving together to achieve a common objective — to produce a superior, economical stand of black spruce that will enable people using those trees to compete effectively on the world markets.

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Seedling-Water Relationships After Outplanting

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Abstract

Since over 125 million coniferous seedlings are planted annually in Ontario, it is essential that both the survival and early growth of the new plantation crops are optimal.

As most plant physiologists and silviculturists consider dessication to be a primary cause of plantation failure, it is essential to maintain a favorable internal plant water balance after outplanting. This will ensure that the stock becomes **both** well established and grows rapidly so that it can overtop the competition and form a vigorous plantation.

The morphological and physiological condition of nursery stock before outplanting is considered and related to the annual stages of dormancy development and release to accentuate the importance of preparing nursery stock that will regenerate roots rapidly after outplanting, become well established, and continue to grow.

Both soil and plant water relations are discussed and quantified for coniferous seedlings both before and after outplanting. In particular, the relationships between the negative water potential of the soil (ψ_{soil}) and the shoot xylem water potential (ψ_{plant}) of outplanted nursery stock are discussed and quantified.

The role and importance of both transpiration and stomatal conductance of outplanted nursery stock are discussed to show how outplanted stock limit water loss under stress. When stress becomes severe (ψ_{plant} ranges from -1.4 to -2.5 mPa [-14.0 to -25.0 bars]), the stomatal resistance of coniferous stock increases and transpiration declines. When stress becomes very severe (ψ_{plant} ranges from -4.0 to -5.0 mPa [-40.0 to -50.0 bars]) for even a short time, outplanted conifer stock dies.

Résumé

Comme on plante chaque année plus de 125 millions de semis de conifères en Ontario, la survie et la croissance initiale des nouvelles plantations doivent être optimales.

Étant donné que la plupart des physiologistes des plantes et des sylviculteurs considèrent que la dessiccation est la principale cause de l'échec d'une plantation, il est essentiel de maintenir à l'intérieur des plants un bilan hydrique favorable après la création d'une forêt pérenne. Les plants auront alors la possibilité de s'établir solidement et de croître rapidement pour vaincre la compétition et former une plantation vigoureuse.

On examine l'état morphologique et physiologique des plants en pépinière avant la création des forêts ainsi que la relation entre cet état et les phases annuelles d'apparition et de disparition de la dormance afin de souligner l'importance d'une préparation des plants en pépinière qui assure une régénération rapide des racines après la transplantation de même qu'un bon établissement des plants et leur croissance soutenue.

On examine et on quantifie les relations hydriques entre le sol et les végétaux dans le cas de semis de conifères avant et après la création de forêts, en insistant sur les rapports entre les ressources en eau potentielles négatives du sol (ψ_{sol}) et les ressources en sève brute potentielles de la pousse (ψ_{plante}) dans les plants de pépinière utilisés pour la création de forêts.

On analyse le rôle et l'importance de la transpiration et de la conductance stomatique dans des plants de pépinière transplantés en forêt afin de montrer comment ces plants limitent les pertes d'eau en présence de stress. Lorsque ce stress s'aggrave (ψ_{plante} varie de -1,4 à -2,5 mPa [-14 à -25 bars]), la résistance stomatique des plants de conifères augmentent et la transpiration diminue. Lorsque le stress atteint un niveau excessif (ψ_{plante} varie de -4 à -5 mPa [-40 à -50 bars]) même pendant une courte période, les jeunes conifères transplantés en forêt meurent.

Introduction

The more than 125 million coniferous nursery seedlings (63 million bareroot and 62 million container stock in 1985) now produced and outplanted annually in Ontario (OMNR 1986) represent a very large financial investment for the forest companies and government of the province. To protect this investment and to sustain the supply of forest products, it is essential that the stock survives and grows actively to form forest crops that produce maximum returns in the future (COFRDA 1985).

Improvements in the survival and growth of coniferous stock after outplanting (Weingartner 1981, Hambly 1980, Armson 1975, MacKinnon 1974), are needed to increase the effectiveness of the present large-scale reforestation program of coniferous species in Ontario. Research on the environmental and plant factors that affect the survival and early growth of boreal coniferous plantations has not been extensive (Day and Harvey 1984a and b, 1983; Sutton 1983, 1982, and 1980), but preliminary research suggests that the ability to (1) regenerate and extend new roots, (2) absorb water, (3) maintain a desirable water status within the seedling, (4) photosynthesize, and (5) begin to elongate new shoots during the "establishment period" (for 30 d after outplanting) are critical.

As almost every plant process is directly or indirectly affected by water supply, the establishment and growth of outplanted stock depends on available soil moisture and atmospheric stress more than any other site factor (Kramer 1983, Koslowski 1982, Daniel et al. 1979). Water is important to plants because of its role in four basic physiological processes (Kramer 1983):

1. Water is a constituent of cell sap and comprises over 50% of the fresh weight of woody plants such as nursery stock.
2. Water is the solvent in which gases, mineral and other solutes (e.g., carbohydrates) enter plant cells and move from cell and organ to organ.
3. Water is the reactant in which the most important plant processes including photosynthesis occur; insufficient water in the plant reduces or stops the photosynthetic process.
4. Water maintains turgidity which is essential for cell enlargement and growth; turgidity is most important for maintaining open stomata, the regeneration and elongation of

new roots immediately after outplanting, and the elongation of new shoots after establishment.

Adequate soil moisture at the time of outplanting is particularly critical for the establishment of conifers that have suffered root damage if they are to maintain satisfactory internal water status for the above processes.

Morphological and Physiological Condition of Nursery Stock Before Outplanting

The response of nursery stock to the environment after outplanting has been shown to depend on the morphological and physiological condition of the stock at time of planting (Day et al. 1985, Duryea 1985, Ritchie 1984). Acceptable levels of morphological quality have been defined for bareroot stock produced on the OMNR tree nurseries (Day et al. 1985, Day 1985b, Day and Fraser 1986). Unfortunately, the physiological quality of nursery stock has not been well defined. The physiological condition of stock at time of outplanting depends on root pruning, wrenching, lifting, packing, storing overwinter at -2 ± 1°C, storing during the shipping season at +2 ± 1°C, handling in the field, and the outplanting method used (Edgren 1984). If outplanting is to be successful it is most important that the stock is in suitable physiological condition to become established. The basic physiological processes affecting establishment and growth after outplanting are as follows:

1. The patterns of seasonal shoot and root growth, the breaking and setting of buds, and the development and release of dormancy in relation to time of outplanting.
2. The ability to absorb water from the soil and to transport, store, and use it within the plant for transpiration.
3. The ability to absorb mineral elements from the soil and to use, transport, and store them in the plant.
4. The ability to absorb CO_2 from the air for use in photosynthesis, to exchange it for O_2 produced by photosynthesis, and to release CO_2 produced in respiration through the stomata.
5. The ability to synthesize, transport, use, and store carbohydrates, proteins, and fats.

In evaluating nursery stock slated for outplanting it is **most** important to know its exact stage in the **annual physiological cycle**. In the boreal forest the seasonal pattern of physiological change of the three principal conifers used for outplanting is dominated by an abrupt change from a very warm summer to a cold winter and vice versa and by associated induction of and release from dormancy. To date only the physiological cycle for the **shoot growth** of white spruce has been properly investigated (Smith and Kefford 1964, Nienstaedt 1966 and 1967, Harvey 1984). The physiological cycle defined by Harvey (1984) for white spruce on the Thunder Bay nursery (Fig. 1) is as follows:

A) **Dormancy Development Steady State** — This begins when white spruce sets bud in mid-July and ends in late October. During this period the white spruce stock becomes less and less able to break bud and elongate new shoots. Throughout the period the water potential of the stock (ψ_{plant}) decreases owing to a decreasing osmotic potential (ψ_π) and a decreasing turgor potential (ψ_ρ). At the beginning of this period the root growth potential (RGP) is usually moderately high which makes it possible to produce $1\frac{1}{2}+1\frac{1}{2}$ transplant stock on the nursery by midsummer transplanting. As the period advances into August, RGP falls to very low levels but increases again as the end of the period approaches. This makes fall outplanting possible, but not dependable because of low RGP at the beginning of the period and cold soils at its end.

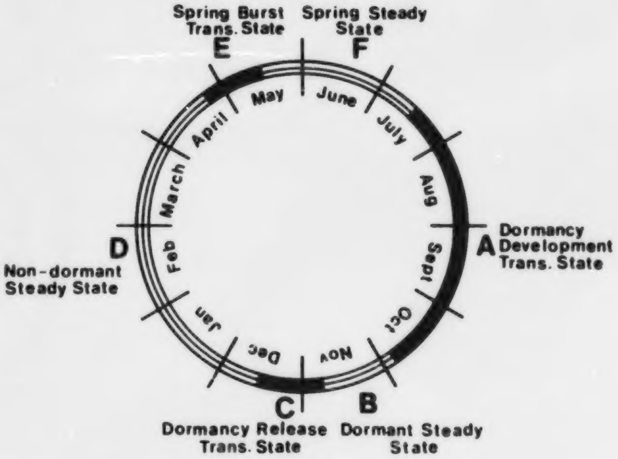

FIG. 1. A diagram of the annual stages of dormancy development and release in white spruce nursery stock (Harvey 1984 and Nienstaedt 1966).

B) **Dormant Steady State** — This begins in late October. During this period the white spruce stock is not able to break bud and the RGP of the stock is very high, but the field soils are too cold for outplanting. Stock is lifted for overwinter storage at the beginning of this period. Provided that the stock has received sufficient chilling to be truly dormant, it can be stored at -2 ± 1°C; if it has not, "freezer damage" occurs.

C) **Dormancy Release Transitional State** — This usually begins in late November and continues to mid-December. During this period the stock changes physiologically and "dormancy release" takes place. After dormancy release the stock will break bud and regenerate roots actively (RGP is high) if it is warmed to > +5°C.

D) **Nondormant Steady State** — This usually begins in mid-December and continues until the stock is warmed up to > +2°C in late April or early May. Throughout this period the stock is ready to grow as soon as the temperature warms to > +2°C. Stock stored at -2 ± 1°C during this period shows a minimal decline in vigor so that its rate of bud break and RGP declines slightly.

E) **Spring Burst Transitional State** — This begins when the snow melts and the soil thaws. It is best to lift stock for cool storage at +2 ± 1°C as soon as possible after the soil thaws to ensure that the stock has not become too active to store. As soon as the soil temperature rises to > +2°C root growth begins slowly in the nursery beds. When the air temperature rises to > +5°C the buds begin to break. The physiological changes that take place during this stage include an increase in ψ_π and in ψ_ρ. These changes rapidly increase the ψ_{plant} of the stock at the time of bud break, and activate most growth processes including root growth. As RGP is very high during this period roots may be elongated on the nursery before the stock can be lifted for outplanting.

F) **Spring Steady State** — The buds break, shoots elongate, and the stock begins to grow in diameter. Stock in this state may be damaged in cool storage at $+2 \pm 1$°C because it becomes etiolated and unhealthy in the dark; instead, it should be "heeled-in" in the field. Because of increasing activity of the stock during this period outplanting success becomes less dependable because of reduced RGP and greater susceptibility to stress.

Knowledge of the exact physiological cycle of each major reforestation species is of great importance for evaluating the RGP and the shoot growth potential (SGP) of stock shipped from the nurseries for outplanting at various times of the year (Day 1985c).

Recent studies have shown that physiological attributes, particularly RGP, SGP, and ψ_{plant} (or plant Moisture Stress [PMS]) may predict field performance more accurately than morphological attributes (Day et al. 1985; Day and Harvey 1984a and b, 1983; Duryea 1985; Ritchie 1985; Sutton 1984, 1980, 1979; Burdett et al. 1983; Ritchie and Dunlap 1980; Cleary and Zaerr 1980). The status of research in Northern Ontario is as follows:

1. The RGP of $1\frac{1}{2}+1\frac{1}{2}$ white spruce (*Picea glauca* (Moench) Voss) and black spruce (*P. mariana* (Mill.) B.S.P.) and 2 + 0 jack pine (*Pinus banksiana* Lamb.) stock has been shown to correlate with outplanting success (Day and Harvey 1984a and b, 1983; Sutton 1983, 1982, and 1980; Mears 1978; Kenny 1976), but further research is needed to refine the correlations.
2. The SGP of the boreal conifers has been described (Day et al. 1985, deGroot 1981) but has not been correlated with establishment or growth after outplanting.
3. The PMS of the boreal conifers has been defined (Day and Walsh 1980) but has not yet been correlated with establishment and growth after outplanting.
4. To date there has not been any work on the g_S or E_t of any of the boreal conifers.

Initial Root Development After Outplanting

This depends on: (1) the morphological and physiological condition of the nursery stock at the time it is outplanted, (2) the moisture of the soil in which it is planted, and (3) the atmospheric environment during the immediate period after outplanting.

The effect of the soil moisture and atmospheric drought is critical for approximately 30 d after outplanting. During this period the stock either:

1. Regenerates and extends sufficient new roots to become established and grow or,
2. does not regenerate or extend sufficient new roots to become satisfactorily established so that it cannot grow and goes into "check," or dies (Day 1976).

During this period the development of new roots depends on the RGP of the stock at the time of planting and on the ψ_{plant} that the stock can maintain to extend new roots as follows:

1. If the RGP of the stock is low, it is not likely to become properly established, even if its ψ_{plant} remains high (close to -0.5 mPa predawn) because of a moist soil and minimal atmospheric stress after outplanting (note: 1.0 mPa = 10.0 bars).
2. If the RGP of the stock is moderate, so that new roots are slowly initiated and extended over 5–10 d after outplanting, the stock will only become properly established provided that its ψ_{plant} remains high (close to -0.5 mPa predawn) because of high levels of soil moisture and minimal atmospheric drought for 10–15 d or longer. If soil moisture is inadequate or atmospheric drought is severe for 5–10 d or longer after outplanting, stock with a moderate RGP may go into "check" or die.
3. If the RGP of the stock is high so that new roots are initiated and extended immediately after outplanting, likely the stock will become established provided that soil moisture remains adequate and atmospheric stress remains minimal during the short period (7–10 d) needed to regenerate sufficient roots to establish it.

Growth After Outplanting

This depends on: (1) the effectiveness with which the stock has been established (i.e., as discussed earlier), and (2) on the quality of the microsite and land type on which the stock is planted.

The effectiveness with which the stock has been established is obvious when survival is poor, but is less obvious when survival is adequate and growth is poor. At present one of the difficulties encountered in assessing plantations is the lack of information on expected acceptable growth after outplanting, so the tendency is to assume that "green outplants are OK" and "brown outplants are dead." In recent years, the SGP of outplanted stock has been measured 1 yr after outplanting (Day et al. 1985, deGroot 1981) and compared with standards to judge the performance of both outplanting trials at the nurseries and operational outplantings in the field. Standard outplanting performance charts were developed by the senior author for the three boreal conifers (Day et al. 1985) and have just been developed for Great Lakes, St. Lawrence, and boreal conifers produced in the Ontario Ministry of Natural Resources Southern Ontario nurseries (Day and Fraser 1986).

The quality of the microsite and the land type have a significant effect on growth after outplanting. Obviously, the land type to be outplanted must be evaluated and the stock to be outplanted properly matched to it. In addition, the microsites to be planted must provide sufficient soil moisture and nutrients for establishment and early growth. Ideal microsites for outplanting should have:

1. an adequate volume of fresh well-aerated soil to supply sufficient moisture to the roots of the stock for the initial 30-d establishment period,
2. sufficient loam or organic matter to provide adequate water-holding capacity and an acceptable cation exchange capacity (CEC) for both satisfactory early establishment and growth, and
3. an adequate situation (e.g., not overshaded) and microtopographic position (e.g., on mounds) for photosynthesis,
4. freedom from weed competition.

Soil and Plant Water Relations

The measurement of soil moisture before outplanting is essential to determine whether or not the stock will be able to regenerate roots. An effective and simple way to evaluate ψ_{soil} is by using a "Quick Draw" tensiometer (Day et al. 1985). In general, the ψ_{soil} at time of planting should not be less than -0.5 to -7.5 mPa and should remain in that range throughout the period of new root extension. As it is not possible for the tree planting staff to monitor the ψ_{soil} over 30 d after outplanting, it may be more desirable to take soil samples at time of planting and to use local temperature and precipitation data to compute the soil moisture content using the Thornthwaite water balance method (Thornthwaite and Mather 1957) and derive the ψ_{soil} from soil moisture retention curves.

The measurement of PMS (ψ_{plant}) either as shoot or root xylem water potential (ψ_{shoot} or ψ_{root}) of nursery stock before and after outplanting with a pressure chamber (Ritchie and Hinkley 1975) has been comprehensively reviewed by Day and Walsh (1980) and by Ritchie (1984).

The water status (W) of a seedling (or any plant) is the resultant of the imbalance between the rate water is absorbed through the roots (A), the rate it is transpired through the needles (leaves) (E_t), and the amount stored in the seedling (S) as indicated in equation 1:

$$W = (A - E_t + S) \tag{1}$$

In equation 1, S is minimal. Thus during the daytime when temperatures are high and the humidity is low, E_t commonly exceeds A so that the ψ_{plant} of a seedling falls to critical levels of "stress." Although it is normal for the ψ_{plant} of well-rooted stock in moist soil to fall to -1.0 to -1.5 mPa during the day in warm dry weather, such stock returns to a higher ψ_{plant} during the night when the temperature falls and the relative humidity rises to the dew point. As a result, the best time to measure ψ_{plant} is just before sunrise (predawn). If the ψ_{plant} is lower than normal at this time the outplanted stock is under stress. Stock that is under stress predawn will be subject to a rapid fall in ψ_{plant} during the morning and will reach the point at which the stomata close and gas exchange stops early in the day limiting the growth of the stock. When recently outplanted white or black spruce stock come under continuous stress with the ψ_{soil} $<$-0.06 mPa, or jack pine stock with the ψ_{soil} $<$-0.15 mPa, new roots cannot be regenerated or extended (Day and MacGillivray 1975, Day and Butler 1975). As the ψ_{plant} falls, increased stomatal resistance and eventually stomatal closure reduces gas exchange, photosynthesis, and growth. If such a situation is not relieved the stock starves and eventually dies.

Equation 1 shows that the water status of seedlings should be evaluated in terms of their ψ_{plant}, which have two very different components, the turgor potential (ψ_ρ) and the osmotic potential (ψ_π). The relationship between these two terms is given in equation 2:

$$-\psi_{plant} = (+\psi_\rho) + (-\psi_\pi) \tag{2}$$

ψ_ρ is a positive force exerted by the distended cell walls on internal fluids. Thus as seedlings begin to lose water the turgor potential is the first to be reduced and as zero turgor potential is approached the seedling wilts. ψ_π is a negative force that results from the effect of solutes (sugars and salts, etc.) in the sap. Thus the ψ_{plant} of a seedling is the resultant of the "huff" of the turgor potential and the "suck" of the osmotic potential.

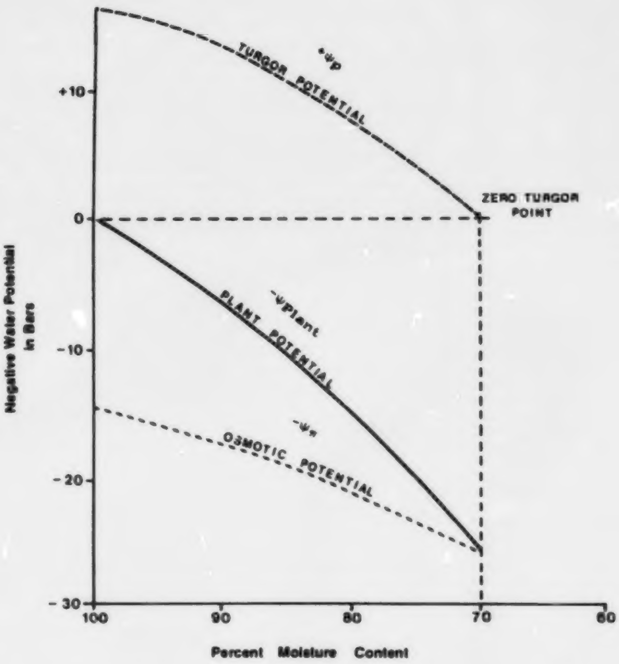

FIG. 2. A typical Hoffler diagram showing the relationship between turgor potential ($+\psi_\rho$), osmotic potential ($-\psi_\pi$), and plant water potential ($-\psi_{plant}$) (Ritchie 1984).

The relationship between turgor and osmotic potential may be illustrated by plotting a Hoffler diagram (Fig. 2). When a seedling is fully hydrated and growing optimally (at 100% water content) the ψ_{plant} theoretically = 0.0 mPa (actually -0.3 to -0.5 mPa) for black spruce and jack pine (Day et al. 1985) and the value of ψ_ρ is equal and opposite to the the value of ψ_π. As the seedling looses water from this point the increase in solute concentration causes both the ψ_π and the ψ_ρ to decrease. Thus as the seedling is depleted of water the ψ_{plant} falls and stress increases as follows (Ritchie 1984):

1. A minimal and not serious loss of 10% of the seedling water content causes a ψ_{plant} of approximately -0.5 mPa with the ψ_ρ = +1.2 mPa and the ψ_π = -0.7 mPa.
2. A more serious loss of 20% of the seedling water content but not all turgor (e.g., on a hot day) causes a ψ_{plant} of approximately -1.5 mPa with the ψ_ρ = +0.5 mPa and the ψ_π = -2.0 mPa.
3. A very serious and possibly fatal loss of 30% of the seedling water content (e.g., in a severe drought) causes a ψ_{plant} of approximately -2.5 mPa with the ψ_ρ = 0.0 mPa and the ψ_π = -2.5 mPa. When the ψ_ρ falls to 0.0 mPa for even a short time the seedling is technically dead.

As the ψ_{plant} of stock shipped in the spring from the Thunder Bay Nursery between 1974 to 1979 ranged from -0.22 to -2.70 mPa for white spruce, -0.19 to -2.70 mPa for black spruce, and -0.10 to -1.58 mPa for jack pine (Day et al. 1985), it is possible that stock is occasionally outplanted at excessively low levels of ψ_{plant}. In general, the ψ_{plant} of stock shipped in the spring from the Thunder Bay nursery tends to be lower at the beginning of the shipping season in late April and early May because its ψ_π is still low. As the shipping season advances, its ψ_π increases as the stock becomes active and ψ_ρ increases even more as the sap begins to run. To date the ψ_{plant} of shipping stock has not been correlated with survival and growth after outplanting.

The procedures for measuring the ψ_{plant} of coniferous nursery stock, particularly white and black spruce and jack pine, with the pressure chamber (Ritchie and Hinkley 1975) are fully described in Day et al. (1985) and Day and Walsh (1980). Day and Walsh (1980) measured the ψ_{plant} of well-rooted nursery stock in beds that were irrigated to $-\psi_{soil} > -0.05$ mPa and correlated it with both air temperature in °C and VPSD. They developed a simple "PMS Calculator" that can be used to adjust measurements made at any time of day to predawn values and to determine whether the stock is the Normal = -0.5 to -1.25 mPa, Moderate = -1.26 to -2.0 mPa, High -2.01 to -2.75 mPa, or Excessive = -2.76 to -3.50 mPa range.

Considerable research has been carried out on the relationship between the plant ant the survival and growth of seedlings after outplanting (Day et al. 1985, Ritchie 1984, Day and Walsh 1980, Clearly and Zaerr 1980, McDonald and Running 1979, Clearly 1968, Pierpoint 1967). Cleary and Zaerr (1988) indicate that nursery stock that is subject to a $\psi_{plant} < -2.0$ kPa should be destroyed before outplanting because of root damage. They also state that photosynthesis slows between -1.0 and -2.0 mPa and is completely stopped from -3.0 to -5.0 mPa. Others have confirmed that the critical ψ_{leaf} for stomatal closure in conifers lies between -1.4 and -2.5 mPa (Beadle et al. 1978 and 1979, Lopushinsky 1969) and that seedlings die when the ψ_{plant} exceeds the -4.0 to -5.0 mPa range (McDonald and Running 1979).

The measurement of ψ_{plant} is an excellent diagnostic tool for assessing internal water deficiencies of nursery stock caused by poor packing, storing, and handling practices **both** at the nursery and en route for the planting site or field storage **and after outplanting in the field**.

Transpiration

E_t is the loss of water vapor from plants. E_t can be regarded as the dominant process in plant-water relations because it controls the rate of water absorbtion from the soil and the ascent of the sap. The E_t rate is determined by the amount of energy incident on the plant available for vaporizing water, the difference in water vapor (density) within the leaf and in the surrounding air, and the resistance to the diffusion of water vapor from the leaf (mainly stomatal resistance) (Kramer 1983).

Energy is supplied to the leaves of plants from direct, reflected, and reradiated insolation and from the flow of heat from the surrounding environment. The water vapor (density) gradient between the leaf and the surrounding air is controlled by leaf temperature and the vapor pressure of the surrounding air (Kramer 1983). The resistance to diffusion from the leaf, which is mainly controlled by plant characteristics, is in three components: (1) stomatal resistance, which is the most important, is a function of the size and frequency of the stomata and their degree of opening; (2) boundary layer resistance which is a function of the water vapor adjacent to the leaf surface acts in series with stomatal resistance and is affected by wind and leaf size (negligible in conifers); and (3) cuticular resistance which is constant for most plants and relatively high (negligible in conifers) (Salisbury and Ross 1985, Ting 1982).

Stomatal Conductance

Stomatal conductance (g_S) which is the inverse of stomatal resistance (g_r) has been defined as "the proportionality parameter relating the flux of water vapor through the stomatal pore to the driving force" (a typical scientific definition) (Jarvis and Morrison 1981). Thus when the stomatal aperture is large, g_S is high and g_r is low and vice versa.

The stomatal aperture is influenced by internal plant factors (e.g., growth regulators) and the environment affecting the leaf, principally light intensity, internal and external CO_2 concentration, leaf temperature, water availability (ψ_{soil}), and the VPSD (Kramer 1983, Willmer 1983, Burrows and Milthorpe 1976).

In Scots pine (*Pinus sylvestris* L.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and red pine (*Pinus resinosa* Ait.), maximum stomatal opening is achieved at moderate light intensities. The interaction between intercellular CO_2 concentrations and light intensity is complex and varies among species (Kramer 1983). In the light at high CO_2 concentrations the stomata usually close. In the dark stomata open when CO_2 free air surrounds the leaf (Willmer 1983). Jarvis (1980) has suggested that conifers exhibit distinct optimum temperatures for maximum g_S and both high or low temperatures where g_S approaches zero. Temperatures relationships are confounded by other environmental factors (e.g.. VPSD).

The critical ψ_{leaf} for stomatal closure in conifers has generally been reported in the -1.4 to -2.5 mPa range (Beadle et al. 1978, 1979; Lopushinsky 1969). However, Koslowski (1982) has questioned the usefulness of ψ_{leaf} for evaluating g_S because of variation in the stomatal response of plants in various conditions in varying environments.

Of the environmental factors influencing stomatal behavior, low soil temperature and soil moisture are of most interest to the forest manager because they can be improved through responsible crop planning (Day 1985a). Research concerning these edaphic factors generally indicates that the soil water potential (ψ_{soil}) at which transpiration of conifers is reduced ranges as follows:

1. Sitka spruce (*Picea sitchensis* (Bong.) Carr) = -0.02 mPa (Coutts 1981).
2. Swiss stone pine (*Pinus cembra* L.) = -0.04 mPa (Havranek and Benecke 1978)
3. European larch (*Larix decidua* Mill.) = -0.35 mPa (Havranek and Benecke 1978)
4. Ponderosa pine (*Pinus ponderosa* Laws.), lodgepole pine (*P. contorta* Dougl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and grand fir (*Abies grandis* (Dougl.) Lindl.) -0.1 to -0.2 mPa (Lopushinsky and Klock 1974)
5. Norway spruce (*Picea abies* (L.) Karst.) = -0.7 mPa (Jarvis and Jarvis 1963).

The stomatal behavior of outplanted conifers can also be manipulated by conditioning the stock to react more favorably in the field. For example, research by Blake (1983) in a controlled environment indicates that overwinter storage at -3 ± 1°C conditions white spruce stomata to reduce water loss immediately following transplanting.

Recent measurements of the effect of planting and scarification on the g_S of Scots pine (*Pinus sylvestris* L.) seedlings outplanted on typical forest sites in Sweden (Orlander 1986) showed that planted seedlings has a lower g_S than volunteer natural seedlings and that the period required to equalize g_S lasted over 2 yr. The low g_S of planted seedlings was attributed to poor RGP. Based on the results of this study, the measurement of g_S a few days after planting may be considerably valuable for predicting the establishment of outplanted stock.

Conclusion

There is an urgent need for research on the water relations of outplanted stock to improve both survival and growth. In particular, research, technology transfer, and training are urgently needed on the following:

1. The seasonal physiological cycle of each species to be outplanted so that this can be synchronized with the environment at time of outplanting to optimize the probability of effective establishment and growth after planting.
2. The RGP of each species to be outplanted must be evaluated so that stock that is outplanted has the potential to regenerate and extend new roots immediately (within 7 d of planting).
3. The effect of various types of storage on the physiology and ψ_{plant} of each species to be outplanted so that storage methods can be improved and the performance of overwinter frozen stock improved.
4. The PMS or ψ_{plant}, transpiration (E_t) rate, and stomatal conductance (g_S) of each species after outplanting so that both the response of each species to stress and ability to limit stress after outplanting is known.

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Summary

SESSION I. CLIMATIC APPLICATIONS IN SEED AND STOCK PRODUCTION

Climate has and will continue to play a direct role in the definition of genetic populations. Successful regeneration of the new forest is based on our ability to identify and knowingly select genetic characteristics from these populations, to propagate stock within greenhouses and nursery environments, and to translocate this stock to hospitable planting sites.

In each of these phases of development, either in the controlled environment of the greenhouse and breeding hall or in seed orchards and nurseries, climate continues to play a direct and significant role. For example, at the planning level, the relative success and economy of a seed orchard or nursery operation is influenced by the climate (from the macroscale to the microscale). For more effective planning the climate of a particular location should be considered as one of the available resources. In the case of greenhouses and breeding halls, this information can be used to improve the selection of locations with immediate benefit of reducing energy requirements.

Climate is also an essential resource when defining seed-breeding zones integrated with climate productivity zones (productivity is defined as volume by unit area over time). Including climate as one of the selection parameters will provide a sound basis for integrated forest management and planning.

Operational practices within greenhouse and breeding halls or nursery and seed orchard environments are designed, in some cases, to protect or counter the adverse macroclimate conditions. Yet Forest Climate '86 demonstrated a general lack of understanding and the achievement of only a few successful examples of scheduling operational practices in relation to weather and climate. However, the symposium/workshop did identify that the cost/benefit ratio is relatively high in this intensive sector of forestry. The technology is available, and the willingness to integrate this knowledge is apparent. Where greenhouse knowledge and technology exists and has been successfully applied, it is expected that the application of climate technology and its implementation will have an immediate cost-effective impact.

When the cost/benefit ratio is obviously positive, immediate solutions are possible: for example, the implementation of computerized climatic technology in greenhouses and breeding halls with appropriate software designed to effectively integrate climate with day-to-day operations; the integration of climatic productivity zones with breeding zones; the upgrading of the climatic monitoring (dataloggers) at nurseries and seed orchards to schedule operational practices as a function of climate (e.g., synoptic forecasting for lifting, climate-based irrigation scheduling, etc.); and the modeling of seed/stock operational practices and events using historical climate data archives.

Therefore, it is recommended that:

1. education and training courses in climate and its measurement be established to transfer climate knowledge into the seed/stock production sector of forestry;
2. process studies and computer software models be developed to integrate current weather and climate knowledge into day-to-day operations (e.g., climate-based irrigation scheduling and synoptic forecasting for nursery practices);
3. upgrading of all nursery locations with computerized climate datalogging systems and the development of the software to assist current forestry operations. This software will include appropriate computerized models (e.g., for nursery and seed orchard management);
4. genetic breeding zones be integrated with climate productivity zones for forest renewal management, microscale to macroscale climate integration; and
5. interagency team cooperation be encouraged to increase the delivery, effectiveness, and implementation of current climatic knowledge into forestry renewal.

Integrating Knowledge of Climate into Forest Regeneration Discussions

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Abstract

The importance of climate and especially changes in microclimate following denudation in Canada has not been adequately recognized or researched. The status of reforestation and our collective knowledge of the biological and physical environments are reviewed briefly and found wanting. Four examples of recent research at the microclimate level show how reforestation results can be improved.

Foresters need the help of multidisciplinary research teams to make use of existing information and to carry out new research designed to find out how forest regeneration can be carried out more successfully and efficiently. Major objectives for such a team are provided.

Résumé

L'importance du climat et particulièrement des changements microclimatiques après la dénudation au Canada n'a pas encore été étudiée ou reconnue sérieusement. Un bref examen des projets de création de forêts et de nos connaissances collectives sur les environnements biologiques et physiques révèle de graves lacunes dans ces secteurs. Quatre exemples de récents travaux de recherche au niveau du microclimat montrent comment améliorer la création de forêts.

Les forestiers doivent être secondés par des équipes de recherche multidisciplinaires afin d'utiliser l'information existante et d'effectuer de nouveaux travaux en vue de déterminer comment créer des forêts avec le maximum de réussite. On présente dans cet exposé les principaux objectifs d'une telle équipe.

Introduction

The general objective of this symposium is to focus on the importance and impacts of climate on forest management. In this session the emphasis is on forest regeneration. The terms of reference are (1) clarify or define the problem, (2) summarize our state of knowledge, and (3) shine a spotlight on the future.

The focus is "the climate near the ground," or more specifically, from 2 m above ground level to 1 m below. The challenge is formidable. There is a legacy from the past — a neglect of our forest regeneration responsibility that must be corrected. In addition, there is an urgency to change our present management procedures to obviate or minimize future regeneration problems. This requires decision models that integrate biology, climatology, economics, and development and harvesting options to guide the forester. Such models are best developed by a multidisciplinary research team.

Regeneration Planning — Ingredients for Success

The best way to avoid reforestation failures is by having the knowledge to identify the most critical constraints and then make a plan to maximize or at least optimize chance of success (Cleary et al. 1986). In this regard, foresters must consider extremes rather than averages in regeneration planning (Fig. 1). During the preharvest assessment, changes in climate between the forest and an opening must be anticipated. Climatic conditions must be envisioned in our "mind's eye" as they are likely to be during the periods of environmental stress. Summer droughts and heat extremes are not readily evident under the forest canopy. Equally deceptive are the differences in effects of snowpack, or its absence, in winter, and the climate above the snowpack as it melts and exposes the seedling to warm, bright days; cold nights; and drying winds in the spring.

This "mental image" of climatic extremes needs to be quantified for use in developing reforestation prescriptions. These prescriptions must integrate the climatic data and the physiological limits of the species and stock types desired. The availability of data, its relevance to the site, and the degree to which it can be applied form the basis for a successful prescription.

Defining the Problem

On denuded forest land reforestation often fails, or proceeds very slowly and at considerable cost. Of specific relevance to this symposium are the interactions started by the change in the physical environment and the biological response to these changes and their impacts on establishment and growth of the new forest. Specific examples are:

- The change in extremes of climate brought about by tree removal and how this impacts the reforestation process.
- The necessity of developing nursery regimes to produce seedlings adapted to survive and grow under specific climatic conditions.

The scope of the problem and the significance of climate in forest regeneration increase as local climate and climatic differences become more extreme. Interaction between topography and macroclimate can create enormous differences in microclimate within a relatively small geographic area. This is illustrated by the following three scenarios.

MILD CLIMATE

On the west coast of Vancouver Island climate is mild and does not hinder regeneration.

HARSH SUMMER CLIMATE WITH MODERATE WINTER

Forty to 50 km inland on a steep, south-facing slope of 500–700 m elevation the situation changes dramatically. The

TABLE 1. Comparison of macro- and microclimatology observations made in 1942.

Variable	88 Meteorological stations	109 Micrometeorological stations
Maximum annual temp.	33–39°C	24–45°C
Associated time range	July 17–19	April 25 - Sept. 19
Minimum January temp.	−21 to −29°C	−10 to −32°C
Last frost	April 11 - May 11	March 9 - May 24
First frost	Sept. 28 - Oct. 28	Sept. 25 - Nov. 29
Frost-free days	138–197	124–276

The 88 meteorological stations sampled the state of Ohio; the 109 micrometeorological stations sampled one 60-ha watershed in Ohio. The data was collected in 1942.

impact of climatic extremes on seedling survival and growth is significant especially if seedling quality is not high. Concerns now include lethal temperatures at the ground-air interface, soil moisture deficits and transpirational pressures in the summer, and the possibility of freeze desiccation in the winter.

HARSH SUMMER AND WINTER CLIMATE

At 1000 m elevation on the same slope the forester's concerns increase. Soil moisture deficits and maximum temperatures are slightly less severe (Tranquillini 1979, Larcher 1983), but winter extremes (minimum temperatures, soil freezing, radiation effects, etc.) are much more severe. The 800–1200-m zone is one of ecological transition. It is perplexing for the forester because six to nine species — some adapted to warmer, others to colder climates — are found in the mature forest and in the regeneration. All species appear adequately adapted to the site as mature forest. In the regeneration phase, however, some are severely impacted by summer extremes, others by winter extremes.

The foresters need the knowledge to grade or rate units of land according to specific aspects of climatic severity. Secondly, they must know how to make the best possible match of species to each "unit." Thirdly, if planting is prescribed, they must know how to define for the nursery manager the specific attributes needed in the seedlings to be grown for each "unit."

Table 1 (Geiger 1965), based on observations by Wolfe et al. in Ohio in 1942, substantiates the previous generalization. It shows both the range in values between general and specific data, and the wide variation possible in microclimate on a 60-ha watershed. The potential for error if decisions are based on inadequate data is obvious.

Defining the Issues

This symposium is held against an impressive backdrop of neglect and failure in the area of forest regeneration in Canada. Honer and Bickerstaff (1985) provide these estimates for 1977–81:

- Cumulative area of not restocked, productive forest land (NSR) is 21.9 million ha.
- Area denuded each year by man is 750 000 ha; by fire and pests, 1 450 000 ha.

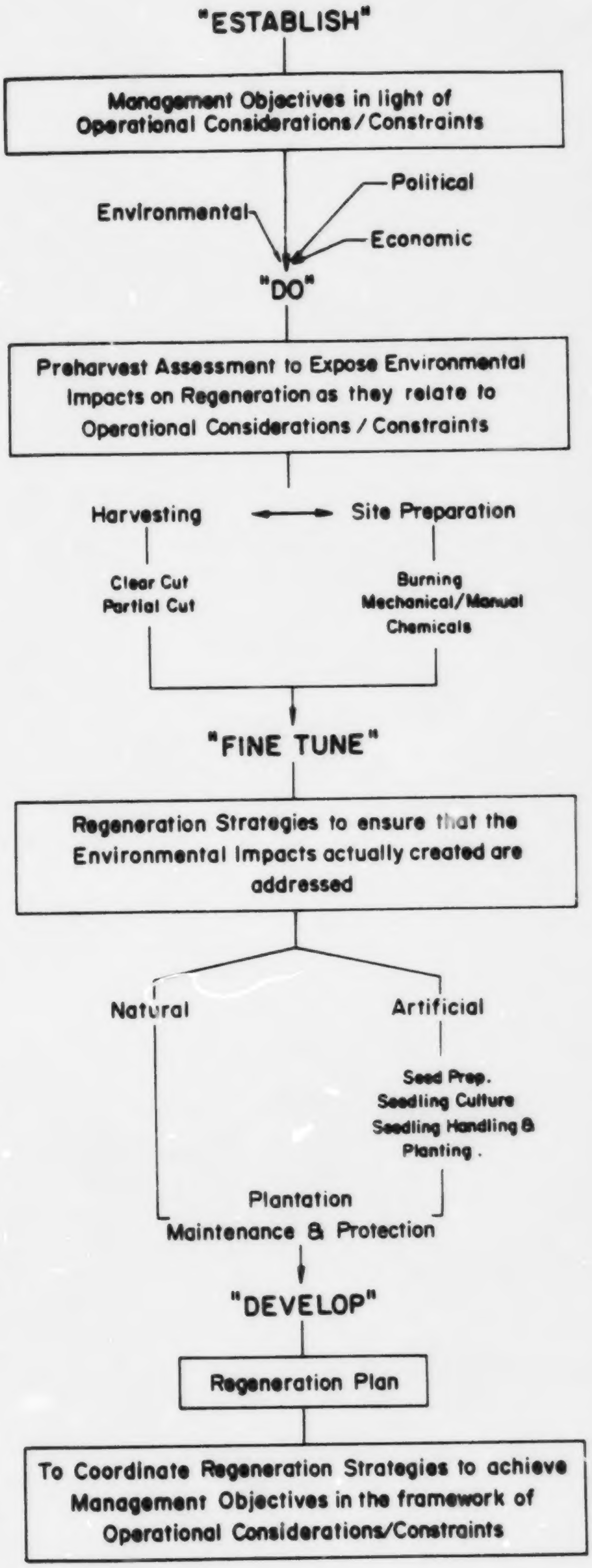
"ESTABLISH"
Management Objectives in light of Operational Considerations/Constraints
Environmental
Political
Economic
"DO"
Preharvest Assessment to Expose Environmental Impacts on Regeneration as they relate to Operational Considerations / Constraints
Harvesting
Site Preparation
Clear Cut
Partial Cut
Burning
Mechanical/Manual
Chemicals
"FINE TUNE"
Regeneration Strategies to ensure that the Environmental Impacts actually created are addressed
Natural
Artificial
Seed Prep.
Seedling Culture
Seedling Handling & Planting.
Plantation
Maintenance & Protection
"DEVELOP"
Regeneration Plan
To Coordinate Regeneration Strategies to achieve Management Objectives in the framework of Operational Considerations/Constraints

FIG. 1.

- Area restocked each year by man is 160 000 ha; naturally, 1 640 000 ha.
- Net annual increase in unstocked land is 400 000 ha.

Were the funds available to inventory this vast area in the next few years and if the job were left solely to foresters, we could certainly get a new and precise inventory that would show:

- area regenerated with commercial species
- area of noncommercial species
- area of NSR.

Further, the forester would have subdivided the NSR into such categories as:

- brushed over, site preparation needed before planting
- not plantable because of slash
- plantable without treatment.

It is unlikely, however, that the report would include a breakdown to show ease or difficulty of restocking based on such physical variables as elevation, aspect, slope, and macro- and mesotopographic descriptors; that is, a breakdown that would reflect the influence of climate. More useful inventories and more effective regeneration will only come about when there is teamwork and cooperation involving the field foresters, the nursery managers, and researchers at the physical and biological levels. Examples of the kinds of questions to be addressed are:

- How can the field forester improve his subjective ranking of restocking difficulty by incorporating macro- and microclimatology knowledge?
- How can we assess causes of regeneration failure more objectively?
- What are our management alternatives for harsher sites?
- How do we best balance the constraints of biology and economics on harsh sites?

This is the backdrop against which this symposium is set.

State of Our Scientific Knowledge

The status of our collective knowledge highlights the differences between forestry as a biological science and climatology as a physical science. Our biological knowledge tends to be qualitative and relative; our climatological knowledge is most often quantitative — averages and extremes. Bringing the two together is the art of forestry. Herein lies the value of cooperation, namely, synergistic rewards.

MEASURING THE BIOLOGICAL ENVIRONMENT — A CASE OF RELATIVITY

The accumulated knowledge of foresters is more qualitative than quantitative. This is particularly true of the knowledge regarding biological factors affecting forest regeneration which has most often been acquired by observation rather than measurement — though this is changing. This knowledge is recorded in general terms; for example, a species response to sunlight results in classification as shade tolerant or light demanding. Where several species can all grow on one site, these observations are refined by ranking; western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) is more shade tolerant than Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) but less so than amabilis fir (*Abies amabilis* (Dougl.) Forbes). To improve our performance, this ranking must be made not on general observation but on physiological response to specific climatic levels.

Building on this knowledge of individual characteristics, numerous attempts have been made to assess and rank the suitability of species to sites with different climates (Landgren and deYoe 1986). Matrices have been compiled that match factors capable of limiting seedling survival (or growth) to different species (Table 2).

TABLE 2. Subjectively ranked tolerances (high to low) of tree species native to Vancouver Island.[a]

Frost	Heat	Drought
Pinus contorta Dougl. var. *contorta*	*P. contorta*	*P. contorta*
Pinus monticola Dougl.	*P. menziesii*	*P. menziesii*
Tsuga mertensiana (Bong.) Carr.	*T. plicata*	*A. grandis*
Abies lasiocarpa (Hook.) Nutt.	*A. grandis*	*T. plicata*
Abies amabilis (Dougl.) Forbes	*P. monticola*	*P. monticola*
Chamaecyparis nootkatensis (D. Don) Spach	*P. sitchensis*	*A. lasiocarpa*
Picea sitchensis (Bong.) Carr.	*T. heterophylla*	*C. nootkatensis*
Pseudotsuga menziesii (Mirb.) Franco	*C. nootkatensis*	*T. heterophylla*
Abies grandis (Dougl.) Lindl.	*A. amabilis*	*P. sitchensis*
Thuja plicata Donn	*T. mertensiana*	*A. amabilis*
Tsuga heterophylla (Raf.) Sarg.	*A. lasiocarpa*	*T. mertensiana*

[a]Adapted by D.L. Handley from compilations by Minore (1979).

Although seemingly handy for the forester, the tool must be used cautiously, for rarely is a ranking based on quantitative data — whether microclimatic or physiological. Instead, the rankings are based on observations of species growing together naturally, or of seedling performance following planting trials. Performance has been measured primarily by survival and height growth and related to climatic data generated at the nearest weather monitoring station. Suspected causes of mortality are normally inferred, for example, a dead tree that grew well initially and then died in midsummer was a victim of drought. Research shows other causes are possible.

At present matrices are far from complete. Not all climatic factors capable of impacting seedling performance are well enough quantified; for example, sensitivity to winter desiccation, soil freezing, sun-on-snow effects, low relative humidity, etc. Obviously, these factors are critical in some cases and must be included to improve the reforestation record.

Sensitivity to geographic origin or seed provenance is also a deficiency of most matrices. Not only can the ability of a species to tolerate a climate extreme change with provenance, the relative ranking of two or more species whose ranges overlap may flip-flop (Landgren and deYoe 1986). This can make the matrix all but useless for those with limited knowledge of regional macro- and microclimates and the species.

Once the species choice is made actual planting must be scheduled to achieve the best possible match of physiological condition of seedling and climate of the planting site. MacMillan Bloedel has developed a basic schedule (Table 3) for broad planning; ideally actual planting starts when soil temperature reaches 5°C and stops when soil moisture tension reaches -1 bars. Nursery lifting (and storage) is

TABLE 3. Time of planting guide for Vancouver Island.

BGC Subzone[a]	Soil moisture deficit starts approx.	Plan to complete planting by
CDFa	April 30	April 10
CDFb	May 15	April 21
CWHa	May 31	May 10
CWHb 3, 4	July 1	June 10
CWHb 1, 2	no deficit	June 10
MH – east side	July 15	June 10[b]
– west side	no deficit	June 10[b]

[a] Biogeoclimatic subzones (Kluika et al. 1984).
[b] If snow present, 3 wk after snowmelt.

scheduled so that seedling physiological development is in step with the climate of each site.

To summarize this section on the biological environment, forest researchers have established a broad base of qualitative knowledge of silviculture. More quantitative measures of some characteristics are becoming available, but are not yet in general use. More quantitative research is necessary before forest regeneration practices can be materially improved.

MEASURING THE PHYSICAL ENVIRONMENT — A CASE OF INADEQUACY

A foray into the realm of published books and bulletins and scientific journals reveals a myriad of measurements on the many components of weather that contribute to climate — from macro- to microclimatic levels. But how available and useful are they to the field forester?

The vast majority of regular weather stations in Canada are poorly sited to meet the needs of forestry. They tend to be concentrated in the metropolitan areas, at airports, and in the towns and villages across Canada. The stations in the smaller centers provide the most useful data but are not representative of forest climate, especially in mountainous areas.

On Vancouver Island, for example, there were 73 active weather stations in 1976: 50 were within 5 km of salt water at elevations of less than 50 m, 15 were more than 5 km from salt water at elevations of less than 150 m, 6 were at elevations of 150–300 m, and 2 were between 300 and 500 m. This dispersion means that the majority of the forest areas — lands over 150 m in elevation, inland from the south and east coast or on north and west coasts — are not served by weather stations.

To make things worse for the forester, the regular weather stations record only the standardized weather measurements and are not concerned with our area of interest, "the climate near the ground."

Fire protection research has resulted in the use of microclimate data as an essential aid to slash burning. Paradoxically, the same foresters do not yet make use of the same stations for fine-tuning planting decisions.

Instrumentation is available for monitoring site microclimate conditions. It is precise and designed for data logging over time. Computer monitoring allows instant acquisition and interpretation of data. Foresters can assess data directly. To apply it, however, they must be able to interpret it within the context of site-specific regeneration problems.

There is an opportunity to interface with forest protection. Increasingly temporary local summer weather stations accumulate data to provide early warning to foresters of high fire hazard and information to guide in prescribed burning (Muraro 1975, Klinka et al. 1984, British Columbia Ministry of Forests 1985). Instrumentation is located to optimize extrapolation of data to nearby operative areas, consequently they are few.

Such developments present an opportunity for both microclimatologists and foresters. This is especially true of Quebec with the well-organized and computerized data gathering systems of the "Societies" which are charged with fire protection responsibility under Quebec law.

To summarize, although considerable macroclimate data is available for Canada, the sources of the data are strongly skewed to population centers and lower elevations and hence are of marginal use for forestry, particularly the regeneration phase. At the microclimate level which has the most influence on the regeneration phase, the knowledge base appears to be limited. This probably reflects a failure to identify its value and lobby for the work to be done.

Benefits of Measuring Seedling Biology and Forest Microclimate

Quantifying the biological capabilities of different species, and families, to deal with the physical characteristics of different microsites is critical to seedling establishment in harsh environments. More importantly, it generates information that forms the basis for developing cultural regimes and preconditioning strategies needed by nursery managers to produce seedlings specifically tailored to conditions on the specific planting sites.

Few cooperative efforts between climatologists and forest biologists have addressed reforestation problems. Where the effort has been made, foresters have gained valuable insight to improving their operational prescriptions.

SEEDLING PROTECTION DURING HANDLING — SOLUTION TO MINIMIZE HEAT STRESS

Seedlings stored in packing bags following processing cannot dissipate heat effectively once warming induces respiratory rise. To prevent overheating, foresters frequently used army canvas to "protect" seedlings. Temperature monitoring of seedlings in bags covered with army canvas revealed a 13°C increase compared with "unprotected" bags (deYoe et al. 1986).

Comparison of a wide array of reflective materials identified a white/silver mylar tarp to be optimally effective in handling radiation — precisely what the climatologist predicted. Seedling temperature following 6-h exposure to incident radiation on a 21°C day was below 15.5°C under the white/silver tarp, 27°C in unprotected bags, and 39°C with army canvas "protection."

Application: The white/silver mylar tarps have been widely marketed during the past 5 yr. Their use is required in the U.S. Forest Service in Region 6 as part of the transport/planting operation. Application of a simple physical principle worked!

POOR SURVIVAL ON HOT, DRY SITES: HEAT-INDUCED MORTALITY

Plantation failures on southerly aspects in southwest Oregon were attributed solely to moisture stress (drought) until quantification of the seedling microenvironment revealed soil temperatures at 4 cm to be over 60°C (surface temperature 70°C) during an August heat spell (Childs et al. 1985). Needle temperatures for Douglas-fir seedlings, however, rarely exceeded ambient air by more than 2°C and pre-dawn plant water potentials were tolerable (Vanderwaal and Holbo 1984). This led researchers to deduce that drought was not the cause of mortality as was generally believed.

Amelioration of temperature at the soil–air interface using natural and artificial shade demonstrated that survival standards for Douglas-fir could be attained (Childs et al. 1985). Shelterwood harvesting provided better protection for seedling establishment than installation of artificial shade guards.

Application: Shelterwood harvesting, where this is feasible and economic, or shade devices, are now being used in areas associated with severe summer microclimates. Although management is more intensive, repeated replants to fix a failure are eliminated and the cost of regeneration is lower.

SUCCESSFUL SPECIES SELECTION — IDENTITY-TOLERANCE TO DROUGHT-HEAT STRESS

Western hemlock, amabilis fir, and Douglas-fir were harvested on steep, southerly aspects at 800–1000 m in the Cameron Valley on Vancouver Island. Regeneration attempts with the same species have met with a low degree of success and some failures.

Careful assessment of water management by seedlings of each of the three species demonstrated that osmoregulating ability was correlated with species survival (Livingston 1986). Osmoregulating ability and hence survival were higher for Douglas-fir than for western hemlock. Amabilis fir did not osmoregulate and had the least survivors even with irrigation and/or shading. Shading improved survival for all three species, with poor osmoregulators benefiting most, but irrigation alone simply delayed and/or reduced development of osmoregulation, increasing the risk of seedling mortality.

Application: The question of species selection for sites where summer moisture can be limiting are better understood. Fewer species selection mishaps should now occur. Strategically amabilis fir and western hemlock are preferred due to superior pulping characteristics, therefore the tolerance limits of these species need to be linked to the site condition and exposure (burned, scarified, moderate slash, brush, etc.) and microclimate differences. Once done this will help foresters predict favorable and unfavorable regeneration possibilities more accurately and allocate species based on the best match with microsite conditions.

UNTOUCHABLE MICROCLIMATE — CREATE FAVORABLE MICROSITES

Cold, damp, thick organic layers hinder spring root growth of white spruce in the interior of British Columbia. The rhizomatous nature of the major competitive species, ladyfern (*Athyrium filix-femina*), thwarts the traditional site preparation efforts. Planted seedlings do not grow due to reduction of light below the photosynthetic compensation point by ladyfern encroachment.

To offset the observed detrimental effects of low light intensity, cold rooting environment, and competition for water/nutrients on seedling survival, spot excavation and mixing of mineral soil and organic matter (mounds) were evaluated on these sites (D. Spittlehouse, pers. comm., from a study currently being conducted by W. Binder et al., British Columbia Ministry of Forests and Lands, Victoria, B.C.; 3 yr of data have been collected and analyzed).

Seedling fine root production increased sixfold in response to the warmer, well-drained rooting environment. Seedling volume growth also increased in the absence of ladyfern; a response to better rooting environment and higher light available for photosynthesis. Frequent summer rain and efficient moisture conservation strategies below -1.5 mPa helped seedlings survive intermittent droughts enhanced by mounding.

Application: Improving the physiological response of white spruce by creating a suitable microclimate provides a method for achieving successful regeneration on these difficult interior sites. Although expensive, preventing planting reentries makes it a cost-effective venture.

Future Direction and Action

Information from climatological data, and/or cooperative studies designed to address site-specific regeneration concerns, is accumulating. Application to reforestation problems requires a conscious effort to integrate research results into practice. Few foresters read scientific journals, and fewer still attend scientific meetings. If the transfer of knowledge is to be successful, the essence of the researcher's results must be presented clearly and succinctly in general forestry journals and bulletins, and demonstrate the economic benefit of biological gain.

Having identified in true Pogo tradition "that the enemy is us," what of the future? Much can be done. The problem is the lack of any obvious mechanism to make it happen.

The forester needs help to identify and quantify the most constraining variables to successful reestablishment and early growth of new forests on problem sites. The importance of this help increases, perhaps exponentially, as the climatic constraints intensify and as the most desired species become less suited to the climatic conditions that exist near the ground before a protective canopy is formed.

Success will only be achieved through cooperation of those committed to working within the framework of operational reality. This requires a mix of basic and applied research. More importantly, it demands continuing interaction with the user groups — those individuals accountable for results from their seeds, seedlings, and forest sites.These objectives are proposed:

1. Identify opportunities to apply existing knowledge and/or technology and test it operationally.
2. Develop baseline information that identifies:
    - site-specific microclimate extremes
    - tolerance limits of desired species/families, and
    - cultural and preconditioning strategies designed to optimize species/family tolerance characteristics
3. Develop a bioclimatological model that can be used to:
    - classify potential regeneration problem areas
    - guide research direction

- integrate research results, and
- improve species/stock-type decisions for all sites and site conditions.

From our perspective a major opportunity exists for the Canadian Forestry Service and Atmospheric Environment Service to cooperate in research and development of models, methods, and technology transfer that will aid the forester in overcoming regeneration problems as effectively as did their cooperation in prevention, control, and management of fire in the forest.

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Forest Land Capability Assessment Using Topoclimatological Survey Techniques

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Abstract

Assessment of the capability of land for forest growth entails multidisciplinary surveys which include climate. While heat, moisture, and light are primary elements governing plant growth, some forest operations are also sensitive to factors like exposure to wind, soil wetness, flooding, snow cover, and snowmelt. Changes to the forest environment incurred in site preparation and the evolution to maturity of the tree crop involve fundamental alterations to the surface energy and water balances (in particular, albedo, the partitioning of net radiation, and hydrological cycle changes: detention storage, infiltration, overland flow, and evapotranspiration). This paper is concerned with the topoclimate during site selection and preparation.

Measurement and monitoring of all climatic processes occurring in the forest are vital research tasks for selected experimental areas, but for general operations simplified and less costly procedures are preferable. The mobile survey technique in which an instrumented motor vehicle is driven over representative terrain under a variety of synoptic conditions provides much useful local-scale information, from which point climatological measurements may be evaluated. Mobile survey procedures are well developed for elements like temperature, humidity, and incoming radiation, and can be employed for precipitation (snow) and wind surveys. However, in regions with poor road networks the usefulness of the method is limited but can be supplemented by remote sensing (nocturnal surface temperatures, snow cover, snow water equivalent, and soil moisture).

Local-scale forest climate classifications can be attempted with useful local information. Even simple rankings of discrete ranges of growing degree-days, flooding, or excessive dryness hazards constitute useful management information.

Results from a field study of station representativeness now in progress near Thornbury, Ontario, are utilized to discuss these concepts, and their relations to land capability. Capability should be assessed using measured climatological data and not inferred from natural evidence without calibration. Periodic reassessments may be desirable because of climatic change and land-use change.

Résumé

L'évaluation des possibilités des terres pour la croissance forestière nécessite des relevés multidisciplinaires incluant des observations climatiques. Bien que la chaleur, l'humidité et la lumière soient les principaux éléments qui déterminent la croissance des plantes, certaines activités forestières sont également vulnérables à des facteurs comme l'exposition au vent, l'humidité du sol, l'inondation, l'enneigement et la fonte des neiges. Les modifications de l'environnement forestier causées par la préparation du terrain et l'évolution du peuplement forestier vers la maturité comportent des changements fondamentaux dans les bilans hydriques et énergétiques superficiels (en particulier l'albédo, la répartition du rayonnement net et les modifications du cycle hydrologique: emmagasinement temporaire, infiltration, écoulement en surface et évapotranspiration). Cet exposé examine le topoclimat lors de la sélection et de la préparation des terrains.

La mesure et la surveillance de tous les phénomènes climatiques qui surviennent dans la forêt constituent des travaux de recherche fondamentaux pour des zones expérimentales choisies, mais dans le cas d'opérations générales, on préfère des méthodes plus simples et moins coûteuses. La technique du relevé mobile, effectué sur un terrain représentatif à bord d'un véhicule motorisé porteur d'instruments, dans diverses conditions synoptiques, permet d'obtenir une information locale très utile, à partir de laquelle on peut évaluer les mesures climatiques. Les méthodes du relevé mobile sont bien rodées pour des éléments comme la température, l'humidité et le rayonnement descendant, et peuvent être employées pour les mesures de précipitations (neige) et de vent. Cependant, dans les régions où un mauvais réseau routier réduit l'utilité de la méthode, cette dernière peut être complétée par la télédétection (températures nocturnes superficielles, enneigement, équivalent d'eau de fonte et humidité du sol).

On peut tenter de classifier le climat forestier à l'échelle locale à l'aide d'une bonne information locale. Même la simple cotation de gammes de degrés-jours de croissance, de valeurs d'inondation ou de risques de sécheresse excessive constitue une information utile pour les questions de gestion.

Les résultats d'une étude sur le terrain de la représentativité des stations, actuellement en cours près de Thornbury en Ontario, sont utilisés pour examiner ces concepts et leurs relations avec les possibilités des terres. Ces possibilités devraient être évaluées à l'aide de données climatologiques qui ont été mesurées et non déduites à partir de phénomènes naturels sans étalonnage. Il pourrait être souhaitable de procéder à des réévaluations périodiques par suite des modifications climatiques et des changements d'utilisation des terres.

Introduction

Plans to afforest a site should include an environmental assessment to determine the natural suitability and likelihood of success. Existing vegetation and other indicators may provide valuable initial information, but the silviculture plan may call for introduction of new species, or a particular plantation configuration different from the present situation. Such a land capability assessment should include climate as well as soil and terrain factors, as they are all primary forcing factors in vegetation establishment and growth. The study of local climate needed to evaluate site selection, preparation, and planting intentions can be complex and costly, but can also be handled economically if the study is carefully matched to the objectives of the scheme. This involves enhancement of regular climatological network information using supplementary stations, mobile surveys, and remote sensing to document important synoptic events. Several means by which these data are obtained are described in this paper.

Climate and Forest Capability

Trees like other vegetation require discrete quantities of light, heat, and moisture for seed germination and growth of the plant. Light from the visible wavelengths of the spectrum (0.38–0.71 μm, Hare and Ritchie 1972) is used in photosynthesis. Overall solar radiation during the growing season is an index of this requirement. Radiation, short- and long-wave, and other energy sources such as advection are needed in the form of heat for plant growth and development. A steady increment of growing degree-days may not be completely satisfactory as plants require "surges" of heat, a few warm days (e.g., >20°C) together to pass phenological stages. Moisture is needed during growth stages to feed the root system and provide turgor to plant tissues. A restriction on available moisture resulting from large evapotranspiration requirements can retard seasonal growth, particularly among seedlings and young trees. These juveniles also need an adequately long growing season to establish roots and foliage. The plantation operator can also improve survival rate by identifying and avoiding strong wind zones, flooding or frequently moist areas and slopes that might become unstable after heavy precipitation.

Established and growing trees produce their own microclimate which can be used to advantage in nursing young trees. However, to reach this level it is important that the seedlings be appropriately sited. Each species has discrete requirements of heat (growing degree-days), soil moisture, an adequate frost-free season, and a long photoperiod. Meagre and insufficient quantities of the climatic resources, or their not being available at the time of year when needed, represent the lower limit of the capability rating. An example is shown in Figure 1, representing available solar radiation for viticultural sites over mountain slopes near Summerland, British Columbia. The suitable range was found to be >3200 MJ/m² with areas ≥4000 being top grade. Slope orientation or aspect is also very important. Similarly, limits may be established for required heat and moisture. This kind of climate capability assessment was developed for agriculture but is adaptable to forestry. Other capability rating schemes have been developed elsewhere, but are also based on heat and moisture considerations (Houzard 1984).

Climatic Variability

Most of this paper is concerned with spatial variability of climate on a local scale, but time variations may also be important. In fact, there are two possible forms of change. There is the change that takes place at the local scale as the seedlings grow and the canopy develops, affecting the kind and amount of radiation at a point, the temperature and humidity amounts and timing, the interception of precipitation, and evapotranspiration opportunity, among other factors. Secondly, there are regional changes caused by external processes, both anthropogenic and geophysical/astronomic in origin. Artificial changes may be the significant ones here, particularly the greenhouse effect from fuel combustion. Increased warmth and atmospheric CO_2 may favor photosynthesis and growth, but negative aspects could include moisture stress and damage from pollutants. There is a general consensus that global annual temperatures are likely to rise 1.5–4.5°C over 90 yr or less (Villach 1985); regional changes may vary. This information could be considered as a strategic element of the silviculture plan.

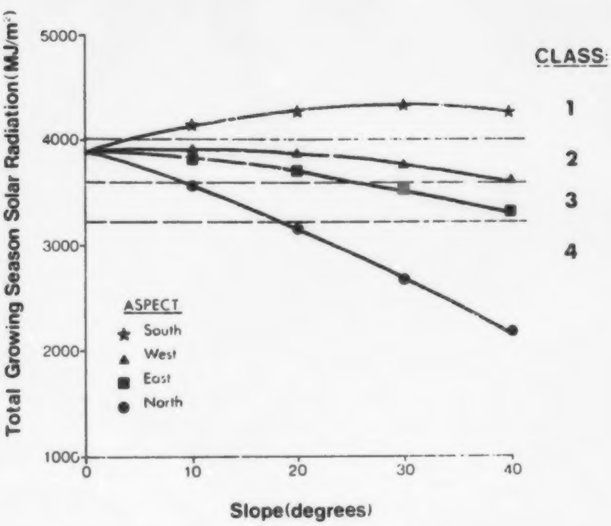

FIG. 1. Total growing season solar radiation (megajoules per square metre) at Summerland, British Columbia, as a function of slope and aspect.

Obtaining Local-Scale Data

Once it is known what the climatic requirements of the proposed plantation are, then the site may be surveyed using a variety of procedures. The interpolation and extrapolation of climate information from established stations to remote areas are done operationally using methods varying from the very simple and crude, to fairly elaborate modeling based on special measurements. Cost and accuracy required are pertinent factors (Findlay 1985).

The standard network of climatological stations is operated with uniformity across the country in terms of instruments, measurement procedures, kinds of sites and exposures as well as spacing of stations. Level, grassy sites with few obstructions (such as trees) are chosen. Thermometers are housed in double-louvered radiation screens at 1.4 m above ground and precipitation gauges are exposed vertically at $\frac{1}{2}$ to more than 1 m above the ground. Wind is measured at 10 m. International standards recommend a spacing of 40 km or less between stations. Standardization enables comparison of data from the network without adjustments for regional or national studies. Standardization of site also eliminates environmental influences on observation time-series.

While a standardized network is fundamental to a meteorological service, other users of climatological data find that they must interpret the information to their respective needs. A simple problem such as a need to know the temperature at a period of the day when there is no measurement may be easily resolved by adding a recording thermometer to the instrument complement. A need to know the temperature at a site distant from the station is handled differently. A second station can be set up or measurements can be made there during the synoptic conditions pertinent to the problem. A mobile survey consisting of fast-response sensors mounted on a moving vehicle can also perform this function, as well as indicate conditions at other localities. Thermal scanners on remote platforms such as aircraft provide similar data from infrared radiation emitted from earth. These near black-body skin temperatures need to be corrected for surface emissivity and adjusted to standard screen height for comparison with regular network stations.

The interpretation of mobile survey data requires an understanding of the ambient weather characteristics or the prevailing synoptic weather type. Greatest contrasts over the terrain occur during dry anticyclonic events, particularly at night when there is strong terrestrial heat loss to the atmosphere and space. Secondly, it is necessary to know and appreciate the processes associated with the local climatic controls. These include elevation changes; slope aspect and steepness; regional water-body influences: their heat exchange, moisture-precipitation, and wind characteristics; topographic configuration; presence and kind of vegetation; soil color and texture; snow cover and/or glaciers. In regions having topographic relief, it is common to distinguish hill-top or plateau, slope, and valley climates. Near water bodies there is a shore climate, defined inland by the penetration of lake or sea breezes. Hill-top or plateau climates are characterized by superior ventilation, lower temperatures, and greater precipitation. Slopes behave according to their exposure to insolation and the prevailing wind, and can have their own circulation resulting from adiabatic heating during the day and subsidence at night. Valleys often have stagnant air trapped in their sheltered lowest portions; they receive cold air drainage at night. Winds parallel to the long axis flush or concentrate excess heat, cold, or pollution.

Conduct of Mobile Surveys

As noted previously, topoclimatological surveys carried out during certain synoptic events (e.g., anticyclones) indicate considerable local variability for most elements. Using a motor vehicle, the instruments being carried are calibrated against measurements at a base station before departure. The vehicle follows a prescribed route stopping at subsidiary stations to check values. Elements like temperature and humidity can be continuously recorded. By using recording instruments like hygrothermographs at the subsidiary stations, adjustments of the survey data to a common time may be done later, so that maps produced depict values for a particular hour. Because of the time correction, the survey should be kept as brief as possible while ensuring the area is adequately covered. In lieu of recording equipment at subsidiary stations, time corrections for diurnal variation can also be made by having the survey routes cross occasionally.

As for precipitation, a method is described in the next section which employs snow surveys stratified by vegetation types to document local variability. This forms part of a case study to illustrate the principles mentioned earlier.

Case Study — Representativeness of Climatological Stations in the Beaver Valley, Ontario

The Beaver Valley is a north-draining valley incised in the limestone of the Niagara Escarpment, west of Collingwood. The rock face has been cut back for nearly 40 km SSW and is 10 km wide at the mouth. The maximum vertical rise from valley bottom to escarpment brow is about 200 m and the valley walls slope at 40 m/km. The topographic variation and the presence of Georgian Bay to the north have produced a variety of local climates. A study was initiated in 1984 to study the extent of these climates which are seen to be typical of many regions, and in particular we wanted to find out where point stations representative of these climate districts could be best sited. For several reasons the data analysis has not received a concentrated effort until recently, and results presented here are provisional.

TABLE 1. Topoclimate Network Beaver Valley.

Station	Region	Location	Elevation (m)
Thornbury Slama	lakeshore	44° 34′ 26″N, 80° 29′ 9″W	214
Heathcote North	lake plain	44° 30′ 10″N, 80° 27′ 37″W	244
Heathcote South	valley bottom	44° 29′ 57″N, 80° 29′ 19″W	233
Kimberley	east slope	44° 26′ 32″N, 80° 31′ 53″W	279
Epping	west slope	44° 26′ 32″N, 80° 33′ 24″W	328
Feversham	plateau	44° 22′ 00″N, 80° 24′ 30″W	436

Earlier work in this area (Findlay 1970) had identified a likely topoclimatic regionalization: (a) plateau; (b) east and west valley slopes; (c) valley bottom (inland); (d) lakeshore. Stations were placed at convenient points within each identified region and a sixth station from the regular network was used (Fig. 2). Table 1 summarizes the physical site and location information for each station.

INSTRUMENTATION OF THE STATIONS

The five special topoclimate stations were set up with identical equipment. Campbell Scientific Model CR21 dataloggers were used to capture and store the data. The dataloggers were programed to store hourly sample values (hourlies), 6-hourly maximum/minimum values (synoptic) and 24-hourly maximum/minimum values (daily). The data were stored on C-60 cassette tapes which were changed every 3 mo. The stations were equipped with wind, temperature (two levels), humidity, and total precipitation sensors. Figure 3 shows the basic setup of the topoclimate station.

The temperature and humidity sensors used were Campbell Scientific Model 101 temperature probe (thermistor) and Model 201 combination temperature/relative humidity probe. The Model 201 probe utilizes a thermistor for temperature and a capacitive element for humidity measurement. The temperature/humidity sensor was housed in a Campbell Scientific model radiation shelter at standard screen height. The Model 101 temperature sensor was placed in a small sandwich type radiation shield at 5 cm to function as a grass temperature and snowpack indicator.

The wind speed and direction sensors used were a Met-one Model 013A 3-cup anemometer and a Met-one Model 023A wind direction vane. These sensors were mounted on a tower at the standard 10-m height.

Total precipitation (rainfall and snowfall water equivalent) was measured by a Belfort Model 5915 weighing-type gauge. The gauges were mounted so that the gauge openings were at 2 m. Alter shields were installed on each gauge to minimize the undercatch. Further corrections based on wind speed were incorporated in the data processing. The gauges were operated over the winter by charging the receptacles with a glycol/oil solution to prevent freezing. Also, the dataloggers and cassette recorders were sheltered in electrically heated environmental enclosures (Fig. 4).

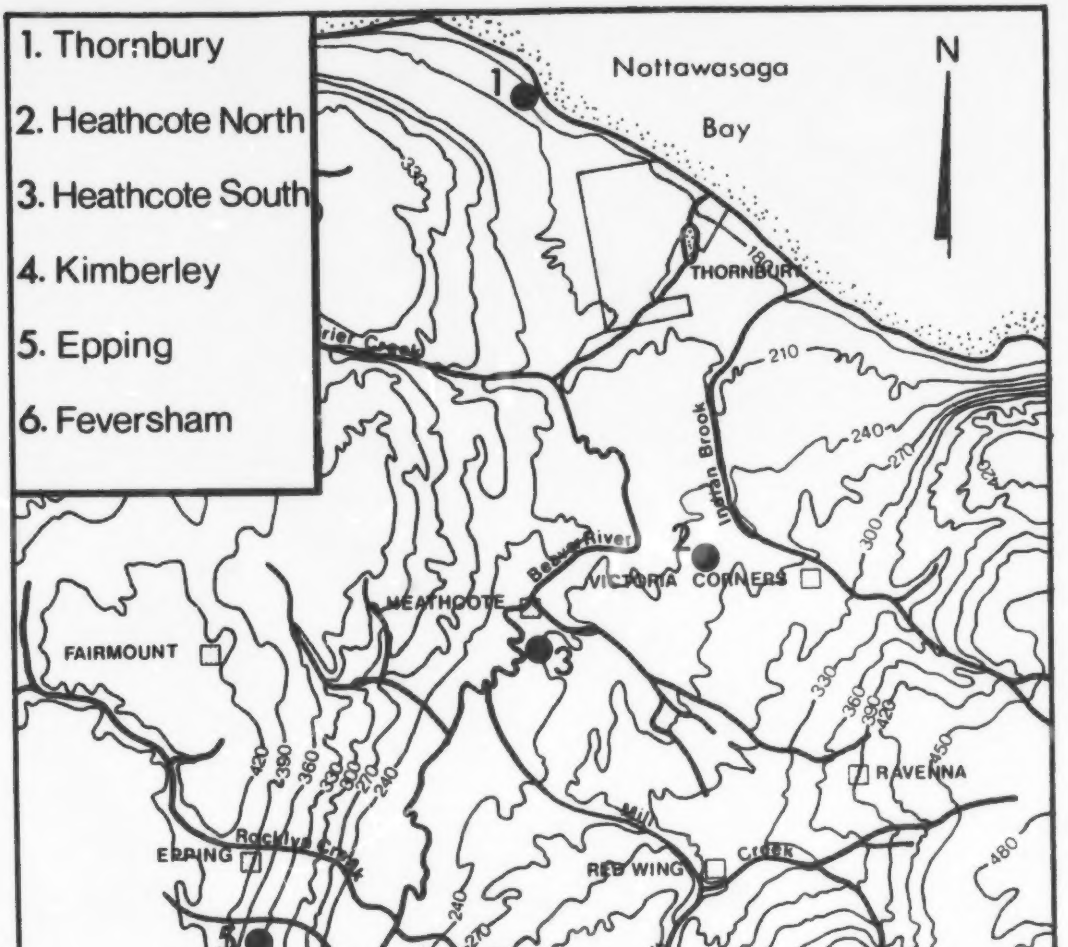
1. Thornbury
2. Heathcote North
3. Heathcote South
4. Kimberley
5. Epping
6. Feversham
N
Nottawasaga
Bay
THORNBURY
Indian Brook
Beaver River
VICTORIA CORNERS
HEATHCOTE
FAIRMOUNT
RAVENNA
Mill
Creek
RED WING
Rocklyn Creek
EPPING
DUNCAN
Mitchell's
Duncan Lake
KOLAPORE
Kolapore Creek
KIMBERLEY
Wodehouse Creek
Black's Creek
Eugenia Lake
FEVERSHAM
0 1 2 3 4
Kilometre
180
210
240
270
300
330
360
390
420
450
480

FIG. 2. Beaver Valley, Ontario, network.

FIG. 3. Heathcote South topoclimate station.

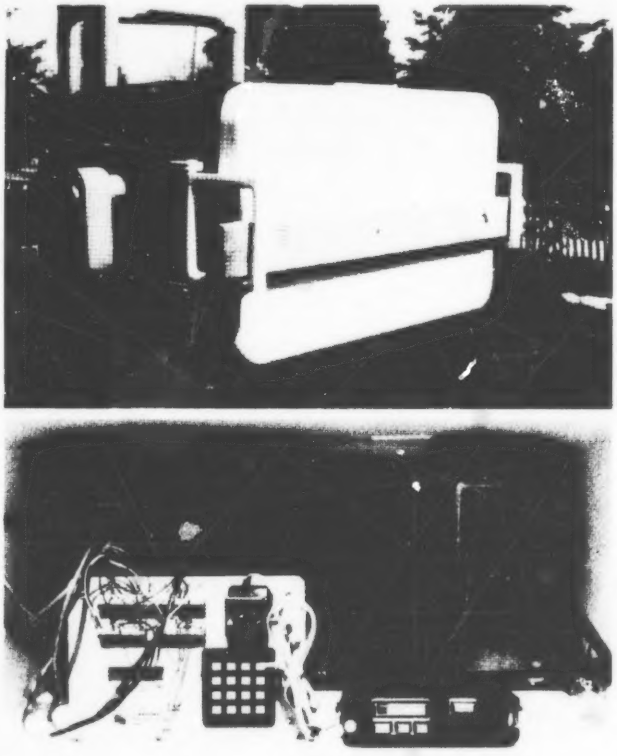

FIG. 4. (*Top*) Environmental enclosure; (*bottom*) interior showing datalogger.

All instruments were calibrated to AES standards before field installation. The regular climatological station at Thornbury serves as a sixth station in the network. This station has twice-daily manually measured temperature and precipitation values. In addition, to provide some indication of airflow at this station a recording anemometer (MRI Mechanical Weather Station) (Fig. 5) was located with the regular station. The anemometer was exposed at 3.5 m, and these data were adjusted to the 10-m level using a logarithmic wind profile model with an assumed roughness length (Z_O) of 0.05.

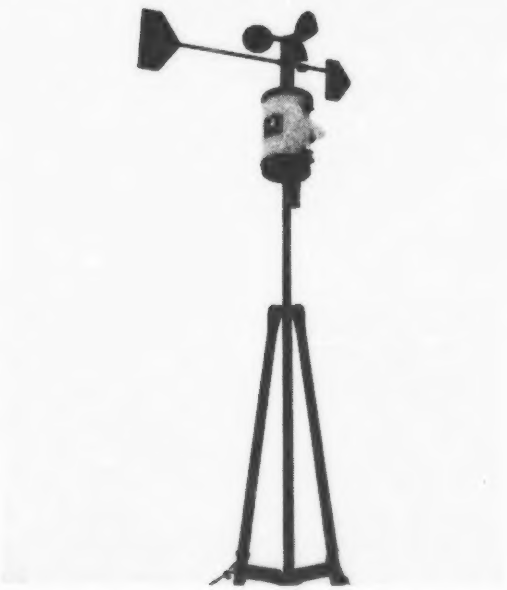

FIG. 5. Mechanical weather station on 3.5-m tower at Thornbury, Ontario.

Climatic Characteristics of the Stations

In Table 2, the mean daily maximum (a), the minimum (b), and the mean daily temperature (c) for each month from September 1984 to May 1986 are listed for the six stations. In part (d) the monthly total precipitation is included. For the most part, the values are expressed as departures from the station at Thornbury.

Over the 21 mo the mean daily maximum temperature on a monthly basis at Thornbury was 0.5°C above normal while the mean daily minimum temperature was 0.2°C below normal.

On a month-to-month basis the differences at the other stations seem randomly positive or negative, but on a cumulative basis, the effects of increasing continentality and elevation inland are evident.

The precipitation figures show a notable decrease immediately inland from the lake. Heathcote North shows a deficit in all months, averaging 34.3 mm/mo. This becomes less at the other stations, and during some months there is greater precipitation than at Thornbury. At Feversham (plateau) precipitation is less than at Thornbury 13 of 19 mo, giving a mean deficit of 13.8 mm/mo. These values are presented here on a provisional basis. As will be noted below, there is likely an overmeasurement of winter precipitation at Thornbury, particularly with respect to the assumed density of lake-effect snowfall. There are other factors to be investigated, including shadow effects at the stations and overall siting regarding areally representative precipitation.

Representativeness of Temperature Measuring Stations

Under many atmospheric states, for example, continuous rain or snow, strong winds, and thick cloud cover, there is very little local variation in maximum daytime or minimum

TABLE 2a. Mean daily maximum temperature (°C).

	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Thornbury 1951–80 (normal)	19.6	13.5	6.2	−0.4	−3.3	−2.8	1.6	9.5	16.1	21.7	24.6	23.8	19.6	13.5	6.2	−0.4	−3.3	−2.8	−1.6	9.5	16.1
Thornbury Sept. 1984 - May 1986	18.2	14.6	6.6	3.0	−5.0	−3.0	3.1	12.2	16.6	19.0	24.3	23.0	21.0	14.0	5.4	−2.5	−2.8	−4.0	5.0	12.4	17.8
Difference	−1.4	1.1	0.4	−3.4	1.7	0.2	1.5	2.7	0.5	−2.7	−0.3	−0.8	1.4	0.5	−0.8	2.1	−0.5	−1.2	3.4	2.9	1.7
Difference from Thornbury 1984–1986																					
Heathcote North	−0.7	1.0	0.3	−4.1	−2.1	−1.5	−2.3	−4.3	−2.8	−3.3	0.1	0.1	−0.2	−2.6	−0.1	−2.1	−3.0	−0.9	−3.0	−3.3	0.4
Heathcote South	−0.2	M	0.9	0.1	1.2	2.2	M	1.5	2.2	2.3	1.8	1.6	1.3	0.5	0.9	1.1	1.0	2.9	1.0	1.3	2.0
Kimberley	1.0	2.9	M	M	0.8	1.9	1.4	1.6	2.7	M	M	1.8	1.5	0.5	0.6	M	0.8	2.2	M	M	M
Epping	0.3	0.9	−0.1	−0.6	0.2	1.5	1.0	0.5	1.5	1.9	0.7	0.9	0.5	−0.2	−0.1	0.1	0.1	1.8	0.8	0.9	1.7
Feversham	−1.9	−0.1	−2.5	−1.9	−1.2	−0.2	0.4	−0.3	1.1	0.2	0.3	−0.4	−0.7	−1.6	−1.5	−1.2	−1.2	0.0	−0.6	M	0.6

TABLE 2b. Mean daily minimum temperature (°C).

	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Thornbury 1951–80 (normal)	11.0	5.7	0.2	−6.4	−10.2	−10.2	−5.6	0.9	6.2	11.8	15.0	14.7	11.0	5.7	0.2	−6.4	−10.2	−10.2	−5.6	0.9	6.2
Thornbury Sept. 1984 - May 1986	9.9	5.8	−0.4	−4.2	−10.8	−9.3	−4.9	1.4	6.6	9.0	14.0	13.6	12.6	5.8	0.5	−7.9	−9.1	−9.5	−4.8	2.2	7.8
Difference	−1.1	0.1	−0.6	2.2	−0.6	0.9	0.7	0.5	0.4	−1.8	−1.0	−1.1	1.6	0.1	0.3	−1.5	1.1	0.7	0.8	1.3	1.6
Difference from Thornbury 1984–1986																					
Heathcote North	−1.6	−1.0	M	M	−2.3	−3.9	−3.8	−3.5	−5.3	−5.5	−6.8	−7.0	−5.5	−7.6	−1.7	−3.6	−4.3	−4.5	−4.4	−4.2	−4.5
Heathcote South	−2.5	M	−0.4	−0.4	−1.0	−1.7	−0.7	0.1	−1.3	−1.3	−2.1	−2.3	−2.0	−3.1	−0.2	−0.8	−1.3	−1.9	−0.9	−1.1	−1.0
Kimberley	−1.6	−0.9	M	M	−1.0	−0.6	−0.5	0.3	−1.0	M	M	−1.9	−2.0	−2.3	−0.2	M	−1.1	−1.0	M	M	M
Epping	−1.8	−1.2	−1.2	−1.1	−1.8	−1.8	−1.2	−0.1	−1.5	−0.7	−1.6	−1.7	−2.0	−2.4	−1.3	−1.5	−2.2	−1.9	−1.7	−1.0	−0.6
Feversham	−2.8	−1.4	−3.0	−2.3	−2.5	−2.3	−2.6	−1.2	−1.4	−1.5	−2.5	−2.6	−2.5	−2.5	−2.1	−2.8	−3.0	−2.6	−2.8	−0.5	−0.8

TABLE 2c. Mean daily minimum temperature (°C).

	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Thornbury 1951–80 (normal)	15.3	9.6	3.2	−3.4	−6.8	−6.6	−2.0	5.2	11.2	16.7	19.8	19.2	15.3	9.6	3.2	−3.4	−6.8	−6.6	−2.0	5.2	11.2
Thornbury Sept. 1984 - May 1986	14.1	10.2	3.1	−0.6	−7.9	−6.2	−0.9	6.8	11.6	14.0	19.2	18.3	16.8	9.9	3.0	−5.2	−6.0	−6.8	0.1	7.3	12.8
Difference	−1.2	0.6	−0.1	2.8	−1.1	0.4	1.1	1.6	0.4	−2.7	−0.6	−0.9	1.5	0.3	−0.2	−1.8	0.8	−0.2	2.1	2.1	1.6
Difference from Thornbury 1984–1986																					
Heathcote North	−0.5	0.0	−0.1	−3.7	−2.8	−2.7	−3.1	−3.9	−4.0	−4.4	−3.4	−3.4	−2.8	−5.1	−0.9	−2.9	−3.6	−2.5	−3.7	−3.7	−2.0
Heathcote South	M	M	0.3	−0.2	0.1	0.3	−0.2	0.8	0.5	0.5	−0.2	−0.3	−0.3	−1.3	0.3	0.1	−0.1	0.7	0.1	0.1	0.5
Kimberley	−0.3	0.3	M	M	−0.1	0.7	0.4	1.0	0.9	M	M	0.0	−0.2	−0.9	0.2	M	−0.1	0.8	M	M	M
Epping	−0.8	−0.1	−0.6	−2.3	−0.8	−0.1	−0.1	0.2	0.0	0.6	−0.7	−0.4	−0.7	−1.3	−0.7	−0.8	−1.0	0.2	−0.8	0.0	0.6
Feversham	−2.1	−0.7	M	−2.1	−1.9	−1.2	−1.5	−0.7	−0.1	−0.6	−1.6	−1.5	−1.6	−2.0	−1.8	−2.2	−2.1	−1.1	−1.7	M	−0.1

TABLE 2d. Mean daily minimum temperature (°C).

	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Thornbury mean monthly total precipitation 1951-80	74.9	73.1	82.5	88.1	69.9	53.6	50.4	55.3	49.5	62.3	65.9	100.9	74.9	73.1	82.5	88.1	69.9	53.6	50.4	55.3	49.5
Thornbury monthly total precipitation Sept. 1984 - May 1986	131.0	59.0	83.6	96.4	133.6	93.6	84.0	65.2	102.0	43.4	58.8	129.8	140.6	99.4	123.3	110.8	85.6	50.2	73.4	82.6	71.0
Difference	56.1	−14.1	1.1	8.3	63.7	40.0	33.6	9.9	52.5	−18.9	−7.1	28.9	65.7	26.3	40.8	22.7	15.7	−3.4	23.0	27.3	21.5
Monthly total precipitation difference from Thornbury 1984-86																					
Heathcote North	−48.0	−27.1	−6.3	−23.4	−90.5	−13.4	−2.0	−7.5	−24.1	−23.5	−0.9	−58.4	−88.0	−29.8	−43.7	−77.2	−47.8	−25.1	−39.8	−21.6	−21.4
Heathcote South	−46.9	−36.9	8.0	−13.3	−32.8	−11.5	23.4	9.4	−31.1	−16.6	−19.4	−49.5	−23.3	−26.8	−26.9	−61.2	−43.8	−17.9	−19.5	−11.3	−17.6
Kimberley	−47.6	−18.3	17.3	9.5	−74.0	−3.6	21.7	M	0.0	0.6	−0.7	−0.4	M	−14.8	−21.9	M	−36.9	−6.7	−16.4	−25.6	−25.6
Epping	M	−18.8	M	M	M	M	M	M	−31.0	−10.3	−10.3	−18.9	M	−5.8	−5.3	−50.4	−35.7	−7.7	−9.4	2.1	−19.7
Feversham	−25.9	−19.9	27.2	26.7	−85.2	7.2	37.1	M	−33.6	−16.4	−18.3	−24.5	−40.2	−24.3	6.4	−6.4	−32.5	−21.7	−18.6	0.6	M

nighttime temperatures. By contrast, the clear sky, low humidity, and light wind situations provide notable interstation contrasts, particularly in diversified terrain. These latter conditions are important to many activities, as they are associated with extremes of cold and heat.

A survey of the frequency of these conditions from September 1984 to May 1986 was made using the hourly meteorological observations at Wiarton, Ontario, to select cases. We looked for persistent clear or scattered cloud cover conditions during both the afternoon and early morning periods and identified a total of 139 cases, representing 11% of the study period. The temperature response at each of the topoclimate stations was noted as a departure from the lakeshore station at Thornbury. As a consequence of missing data the number of cases was reduced. The remainder were segregated into subcases to represent nighttime and daytime situations of off-land and off-water wind, and time of year (water warmer or colder than land). The water temperatures were obtained from satellite-derived data collected by the Hydrometeorology Division of the Canadian Climate Centre.

Twelve combinations are theoretically possible as described below:

Time of day	Water temperature	Wind direction
night	greater than land	off lake
day	less than land	off land
	equal to land	

For cases where water and land temperature differences were small, the cases were combined, and in some categories, for example, daytime, off-land flow, water temperature greater than land temperature, there were no examples or very few. Seven classes were identified, each with sufficient cases for analysis. A total of 91 cases were used.

We decided to exclude all of the shore plain (Heathcote North) values here. The record showed the minimum and maximum temperatures to be considerably lower than at the other sites. Further information is needed to determine whether there is an instrument fault, or whether the site is anomalous.

Regarding the nighttime cases it seems generally evident that there is a broad 1–3°C lower temperature value inland, compared with Thornbury, 50% of the time. The coldest areas are the valley bottom and the plateau. The daytime cases show warmer conditions than the shoreline, being greatest in the shelter of the valley bottom, and least on the plateau, where during the off-water cases cooler conditions are suggested.

This simple synoptic typing produces rather noisy data sets. We calculated standard deviations and coefficients of variation of the means of the identified classes. The variances were large, suggesting that the median is a more appropriate measure of central tendency. To determine how representative these point station values are, a comparison can be made with mobile temperature survey results.

Between 1965 and 1969, 26 nocturnal and 3 diurnal mobile temperature surveys were undertaken over the lower Beaver Valley. Some of the results were reported by Findlay (1970) regarding significance for frost. The nighttime anticyclonic off-land flow category is the most significant in terms of local variability and a generalized case is illustrated by Figure 6. This map indicates that the temperature differences from the lakeshore inland agree reasonably well with Table 3.

Two other nocturnal situations denote the complexity of the local climate (Figs 7,8). On November 8, 1967, a northeast wind brought moist air inland from a comparatively warm lake to near Heathcote. Air cooled by radiational heat loss is evident over the higher sloping ground and south of Heathcote. Towards morning lake-effect snow showers developed over the valley. By contrast, on February 1, 1968 warm air advected from the southwest produced a warm valley south of Heathcote. The wind strengthened to 23 km/h by 0300 EST which would be strong enough to break any inversion in the main valley that is oriented parallel to the flow. However, cool areas persisted over the plateau and elsewhere, presumably because of better shelter.

Fewer daytime cases are available for reference. They indicate, however, that the lake breeze case in spring and early summer provides the strongest temperature contrast. A very light wind case is illustrated by Figure 9 (June 10, 1969).

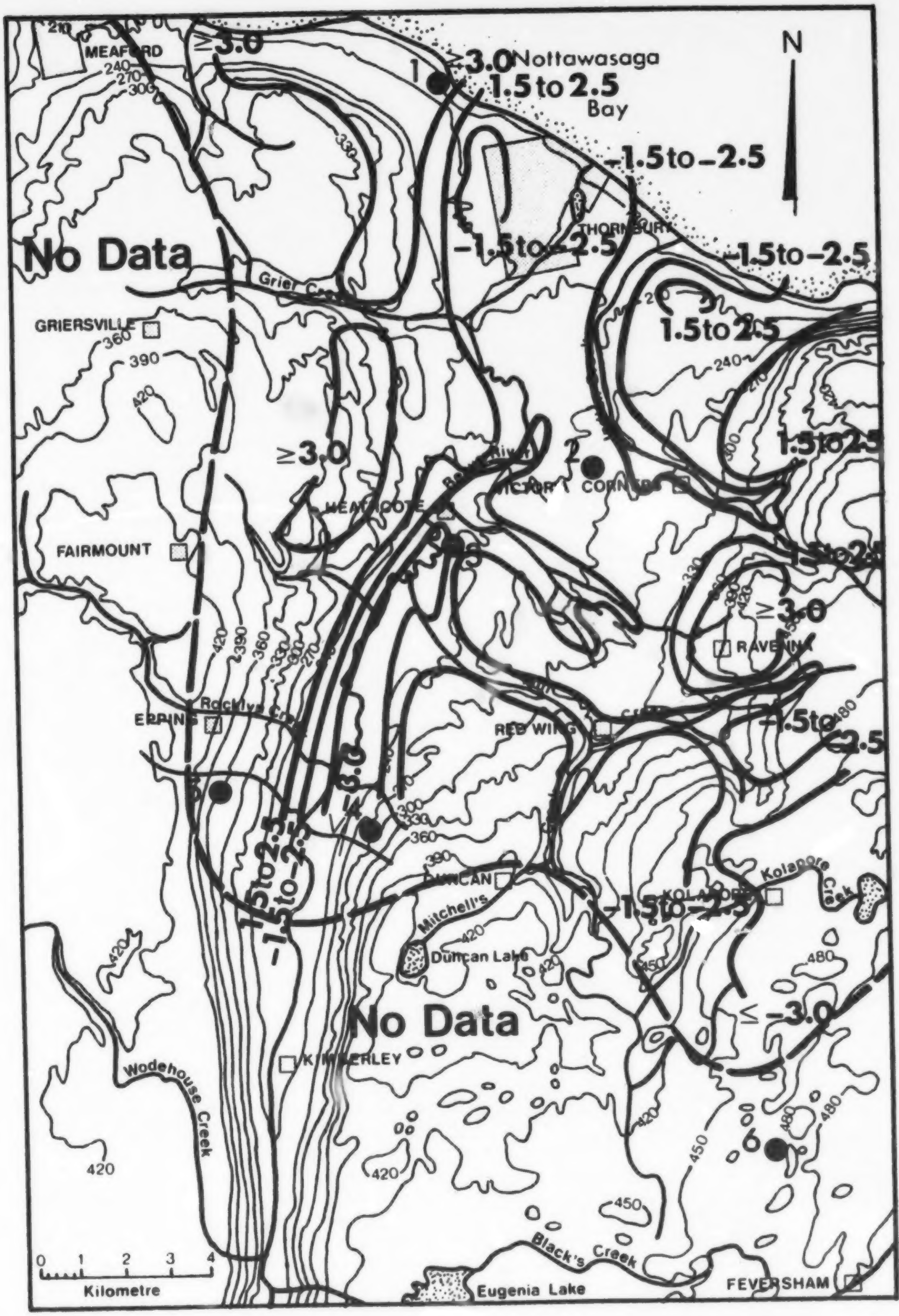
N
MEAFORD
Nottawasaga
Bay
THORNBURY
No Data
Grier Cr.
GRIERSVILLE
HEATHCOTE
VICTORIA CORNERS
Beaver River
FAIRMOUNT
RAVENNA
Rocklyn Cr.
EPPING
RED WING
DUNCAN
KOLAPORE
Kolapore Creek
Mitchell's
Duncan Lake
No Data
KIMBERLEY
Wodehouse Creek
Black's Creek
Eugenia Lake
FEVERSHAM
≥3.0
≥3.0
1.5 to 2.5
−1.5 to −2.5
−1.5 to −2.5
−1.5 to −2.5
1.5 to 2.5
1.5 to 2.5
≥3.0
1.5 to 2.5
≥3.0
−1.5 to −2.5
3.0
1.5 to 2.5
−1.5 to −2.5
−1.5 to −2.5
≤−3.0
1
2
3
4
5
6
0 1 2 3 4
Kilometre

Fig. 6. Temperature (°C) departure from Thornbury, Ontario, nocturnal, off-land winds (nine cases).

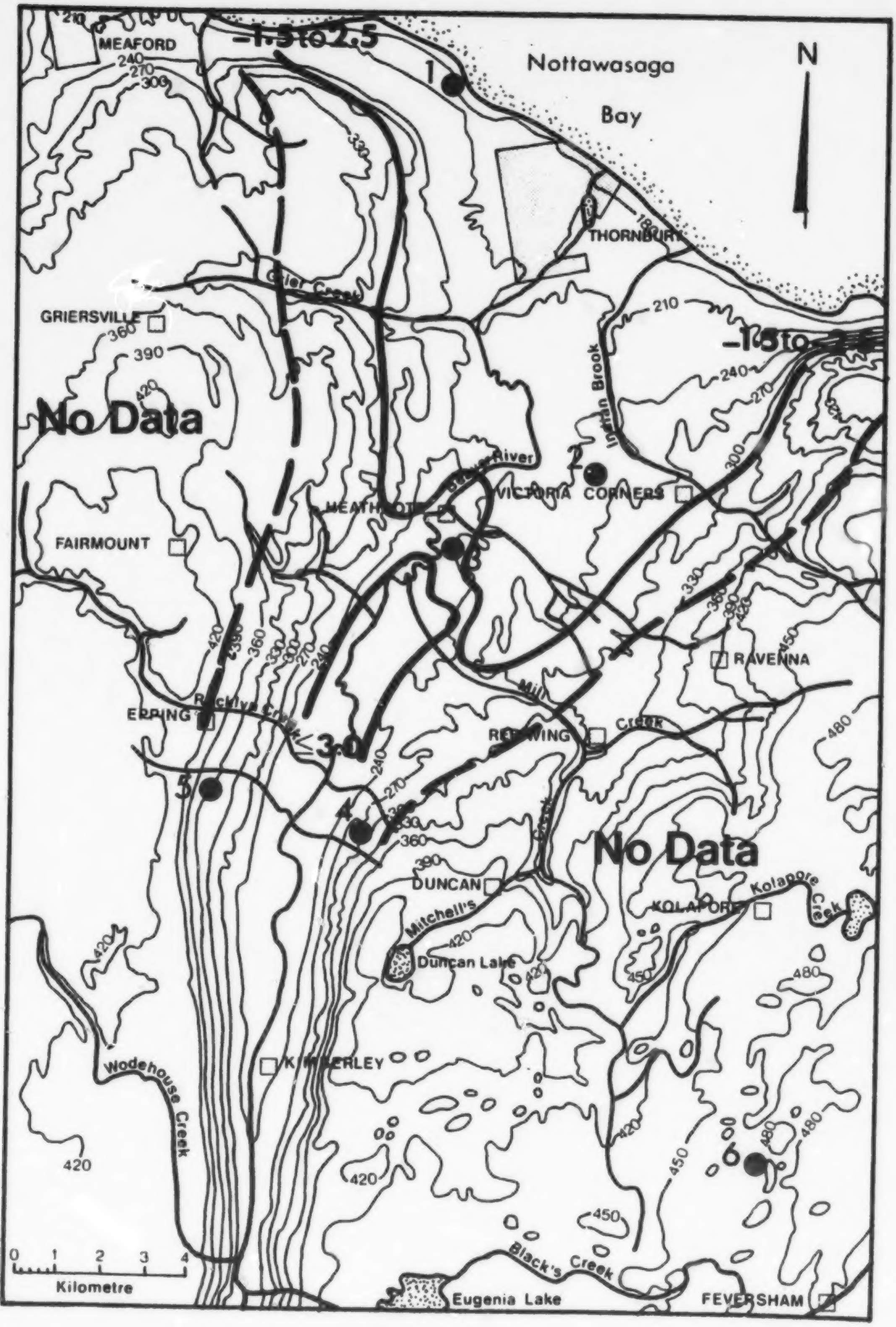
MEAFORD
210
240
270
300
-1.5to2.5
1
Nottawasaga
Bay
N
330
THORNBURY
180
Grier Creek
GRIERSVILLE
360
390
420
210
Indian Brook
-1.5to-2.5
240
270
No Data
Beaver River
2
VICTORIA CORNERS
300
HEATHCOTE
3
FAIRMOUNT
330
360
390
420
RAVENNA
450
240
270
300
330
360
390
420
Mill
Creek
EPPING
Rocklyn Creek
3.0
REDWING
480
5
4
240
270
300
330
360
390
No Data
DUNCAN
KOLAPORE
Kolapore Creek
Mitchell's
420
Duncan Lake
420
450
480
420
KIMBERLEY
Wodehouse Creek
420
450
480
480
6
420
450
420
0 1 2 3 4
Kilometre
Black's Creek
Eugenia Lake
FEVERSHAM

FIG. 7. Temperature (°C) departure from Thornbury, Ontario, November 8, 1967, night.

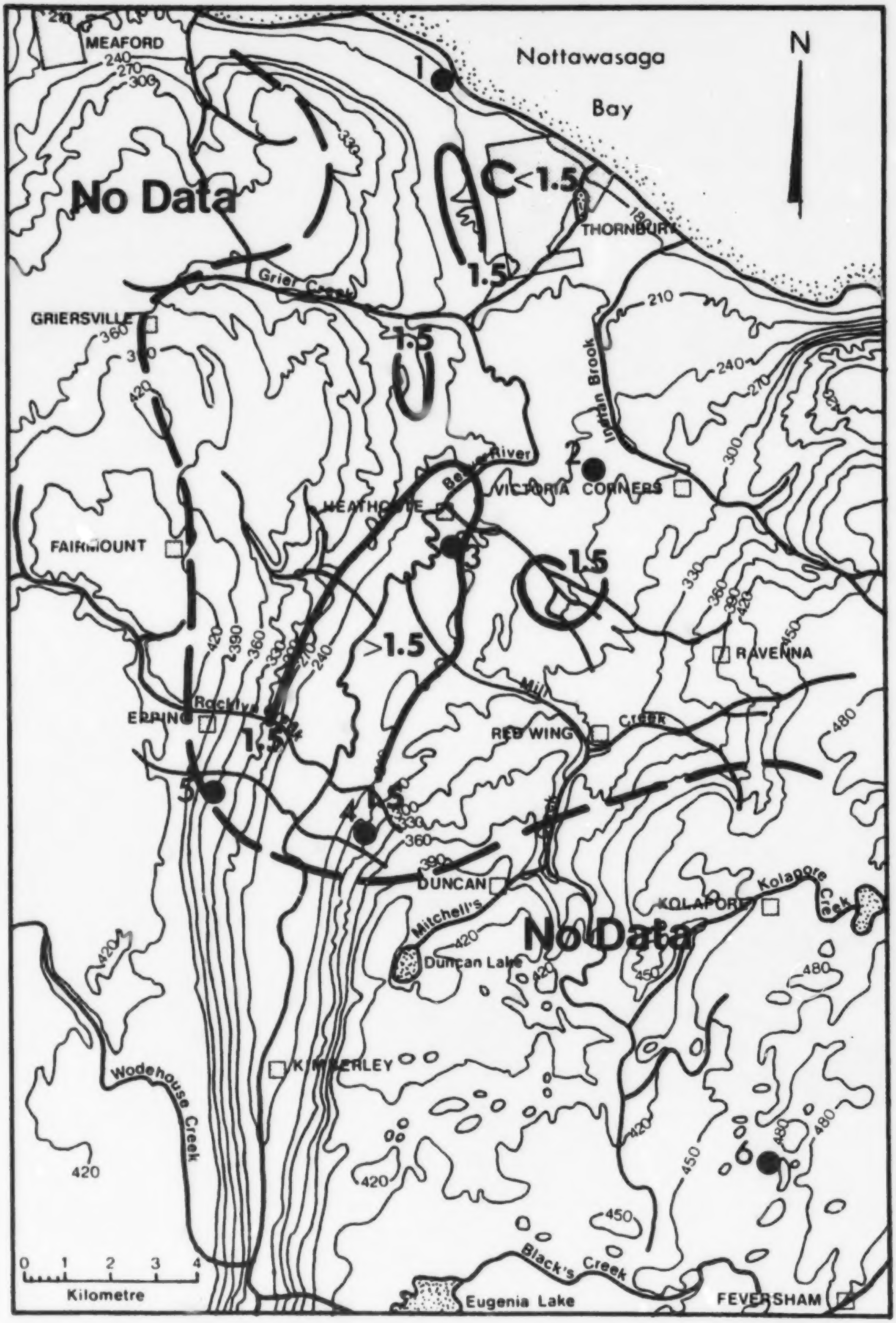
MEAFORD
Nottawasaga
Bay
N
No Data
C<1.5
THORNBURY
1.5
Grier Creek
GRIERSVILLE
1.5
Indian Brook
Beaver River
2
VICTORIA CORNERS
HEATHCOTE
3
1.5
FAIRMOUNT
>1.5
RAVENNA
Mill Creek
Rocklyn Creek
EPPING
1.5
RED WING
5
4
1.5
DUNCAN
KOLAPORE
Kolapore Creek
Mitchell's Creek
Duncan Lake
No Data
KIMBERLEY
Wodehouse Creek
6
Black's Creek
Eugenia Lake
FEVERSHAM
0 1 2 3 4
Kilometre
180
210
240
270
300
330
360
390
420
450
480

FIG. 8. Temperature (°C) departure from Thornbury, Ontario, February 1, 1968, night.

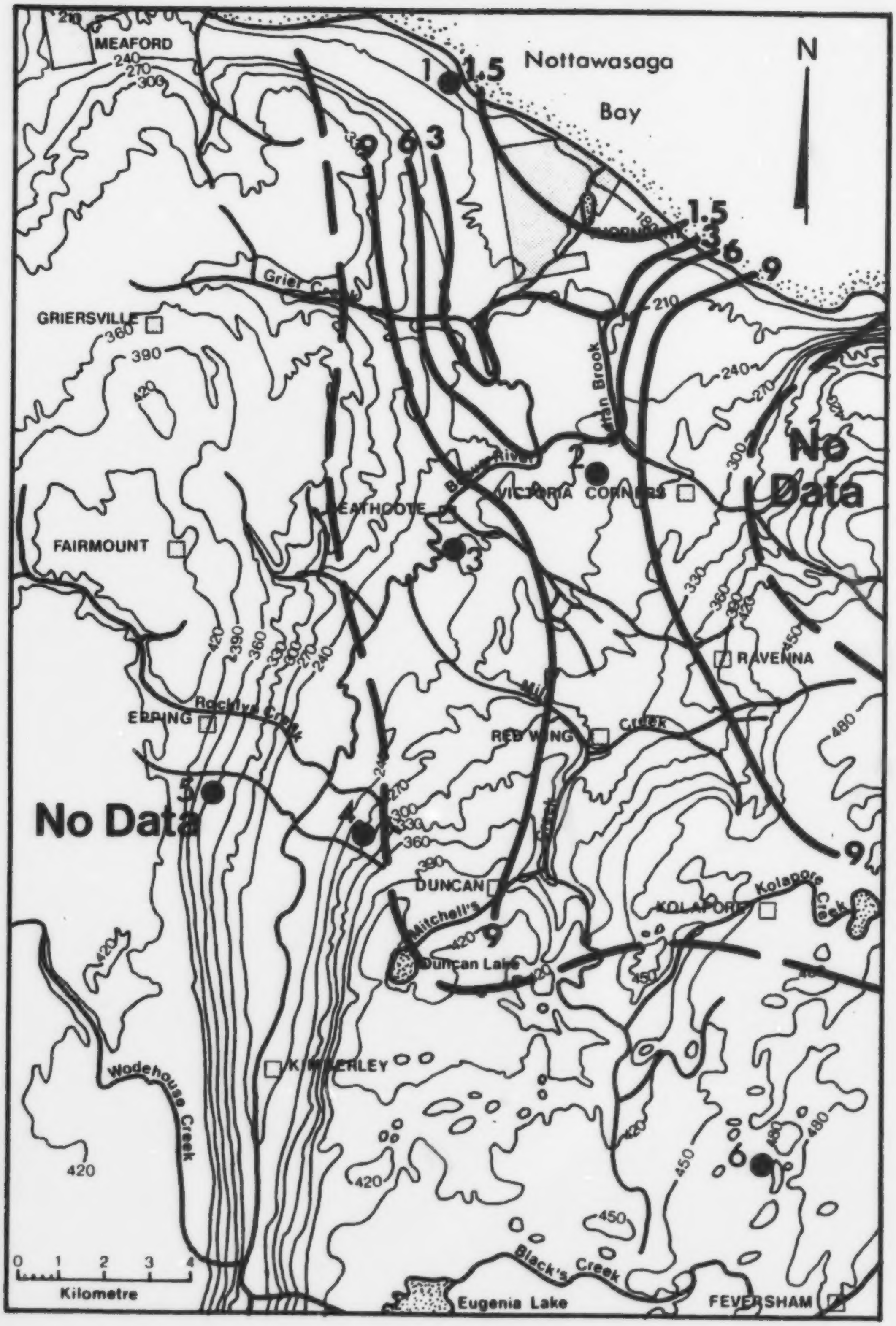
MEAFORD
Nottawasaga
Bay
N
GRIERSVILLE
Grier Creek
FAIRMOUNT
HEATHCOTE
VICTORIA CORNERS
Beaver River
RAVENNA
EPPING
Rocklyn Creek
RED WING
Mill Creek
No Data
No Data
DUNCAN
Mitchell's
Duncan Lake
KOLAPORE
Kolapore Creek
KIMBERLEY
Wodehouse Creek
Black's Creek
Eugenia Lake
FEVERSHAM
0 1 2 3 4
Kilometre
1
1.5
9
6
3
1.5
3
6
9
2
3
5
4
9
9
6
210
240
270
300
360
390
420
450
480

FIG. 9. Temperature (°C) departure from Thornbury, Ontario, June 10, 1969, afternoon.

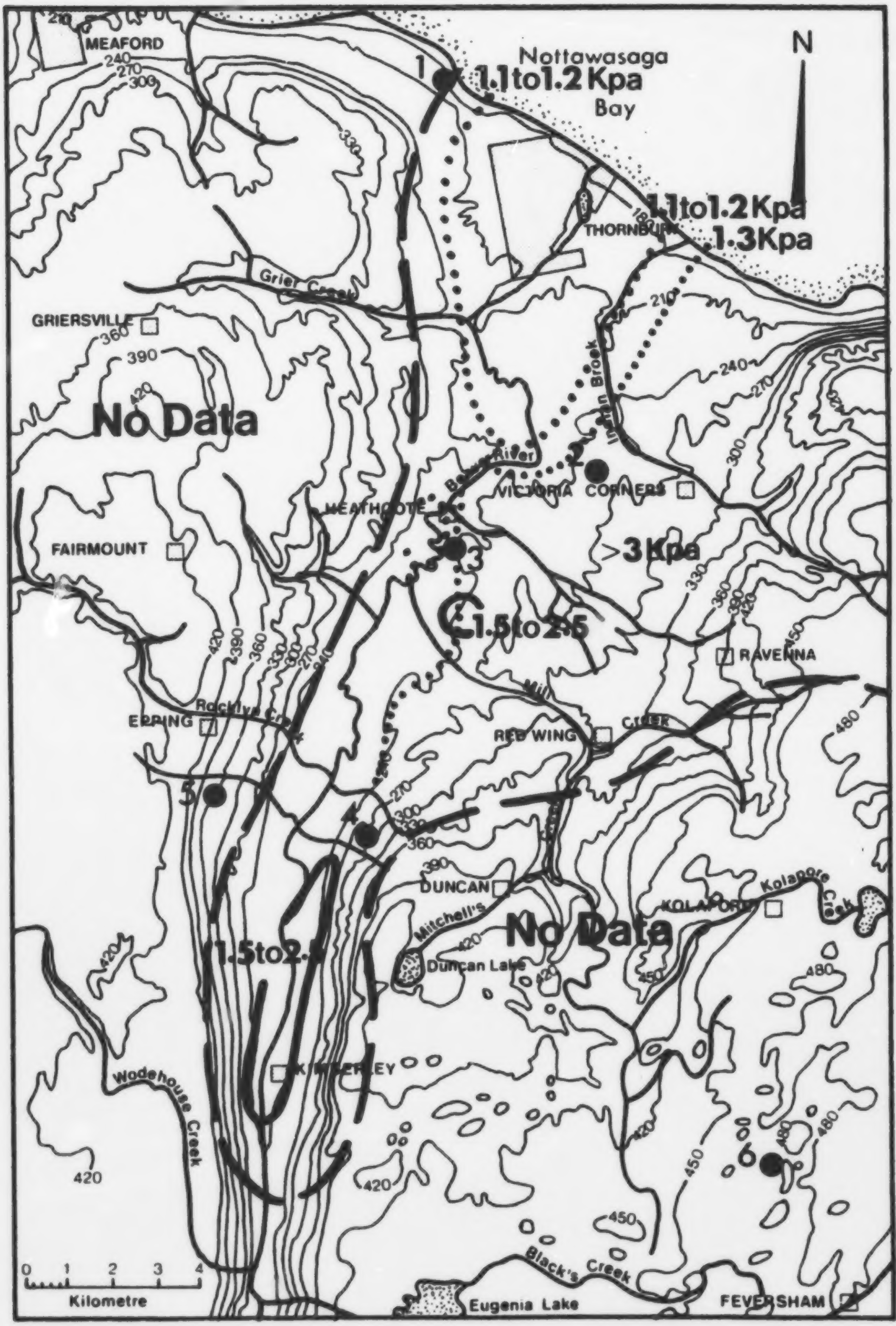
MEAFORD
Nottawasaga
Bay
N
1
1.1to1.2 Kpa
1.1to1.2 Kpa
1.3Kpa
THORNBURY
Grier Creek
GRIERSVILLE
No Data
Beaver River
Indian Brook
2
VICTORIA CORNERS
HEATHCOTE
FAIRMOUNT
3
>3Kpa
1.5to2.5
RAVENNA
Rocklyn Creek
EPPING
Mill Creek
RED WING
5
4
DUNCAN
KOLAPORE
Kolapore Creek
Mitchell's
Duncan Lake
No Data
1.5to2.4
KIMBERLEY
Wodehouse Creek
6
Black's Creek
Eugenia Lake
FEVERSHAM
0 1 2 3 4
Kilometre
210
240
270
300
330
360
390
420
450
480

FIG. 10. Temperature (°C) and vapor pressure (kilopascals) departures from Thornbury, Ontario, August 12, 1969, afternoon.

TABLE 3. Clear sky temperature departures from Thornbury (°C, median values).

		Nighttime			Daytime		
		Water temp. > land temp.		Water temp. < land temp.	Water temp. > land temp.	Water temp. < land temp.	
Station	Water temp. = land temp.	off-water	off-land	off-land	off-water	off-water	off-land
Shore plain	-	-	-	-	-	-	-
Valley bottom	−2.5	−3.2	−2.0	−2.4	+1.6	+2.5	+2.6
East slope	−1.8	−2.1	−1.1	−1.1	+1.8	+2.4	+2.9
West slope	−2.0	−1.5	−1.2	+0.3	+1.8	+1.6	+1.7
Plateau	−1.7	−2.2	−2.1	−0.5	−0.3	−0.3	+1.0
No. of cases (91)	24	7	20	13	5	15	7

A summer case (August 12, 1969) (Fig. 10) indicates very little effect from the lake on land temperature. Some sunny areas sheltered from wind in the upper valley have +1.5 to 2.5° anomalies. Humidity was measured on this day and a weak, but steady, gradient towards higher vapor pressure from lakeshore-inland and to higher elevations was indicated, responding to the capability of warmer air to hold more water vapor.

An off-land case (August 13, 1969 — not shown) showed cooler temperature (-1.5 to -2.5°) in sheltered parts of the upper valley. In summary, a comparison of the temperature zonation indicated by the mobile surveys with Table 3 suggests that the temperature stations are reasonably well-placed.

REPRESENTATIVENESS OF PRECIPITATION STATIONS

Precipitation over an area is characterized by considerable spatial variability compared with other elements. This is not only because atmospheric moisture varies locally, and condensation/precipitation processes act differently, but is also a result of the transport of rain droplets and snow crystals by the wind. In addition, it is a function of precipitation gauge siting and the catch efficiency of the instrument.

There are different ways of checking the representativeness of precipitation stations. Some studies have employed dense rain gauge networks, and it has been shown that gauges oriented normal to the slope in hilly terrain have an improved catch (Hamilton 1954). Other studies have used the hydrological water balance within a discrete basin to determine the effectiveness of precipitation measurements. The present research employs snow on the ground information to assess whether the point precipitation stations are well-sited. Where a snowpack has not been disturbed by major melts during which the snow water drains to ground level, it is possible to measure the water equivalent from the surface down to a known layer, representing the last melt event. Cumulative gauge catch may be compared with these data. We report on the results of two snow surveys here, where the water equivalent of the snow on the ground was measured with vertical samplers of the Meteorological Service of Canada (MSC), and Eastern Snow Conference (ESC 30) types. The samples were bagged and weighed on a laboratory scale at AES headquarters. Provision was made for 44 sampling points plus detailed sampling at five of the climatological stations.

The detailed sampling at the stations consisted of gathering snow cores at five points surrounding the precipitation gauges (N, W, S, E, and C), 20-30 m or more from the gauge. These were compared with the gauge accumulation for the melt-free period. As described previously, the Belfort gauges were equipped with Alter shields and the undercatch error was accounted for (Goodison 1978).

In most instances the gauge values are higher than the averaged ground measurements at the station. Differences of up to 20% are considered modest, representing snow loss at exposed sites by wind transport and by sublimation. In some instances the gauge values are less than the snowpack and this is interpreted to mean that the site is an accumulation zone, following strong winds. Large differences between gauge and pack values represent strong deflation or accumulation, unless there are errors in sampling and instrument performance.

An idea of the representativeness of the stations can be had by comparing departures of nearby snowpacks from the station sites. As Goodison (1977), among others, has shown, the snow retention capability of the surface is influenced by microrelief and vegetation cover. In this instance, differences in grass height would play an insignificant role because we are measuring from a snow crust above the ground. However, some samples have been gathered from orchards and other sites which show anomalies regarding district conditions.

The results of the two surveys are shown by Figures 11 and 12. The earlier survey expressed the cumulative precipitation for January 1985. A rain crust formed on New Year's Day provided the base reference. Persistent cold prevailed during the month and there were several days with strong westerly winds. The ratios of gauge precipitation to adjacent snow water equivalent values varied from a high at the valley bottom site, Heathcote South (1.62), and the lakeshore (1.40), to more modest ratios elsewhere (1.11-1.24). The snow gauge at Epping was inoperative during the period. The high ratio at Heathcote South is explained by the higher snowfall compared with neighboring stations. Much of this snow did not actually accumulate in the gauge, but was computed from the undercatch formula on a daily basis during windy periods. The value may be considered physically reasonable, given processes such as "overspill" from the west during cold air outbreaks. The high lakeshore gauge/ground snow ratio would even be higher if the Thornbury measured precipitation values were used. However, these have been reduced by a factor of 0.7,

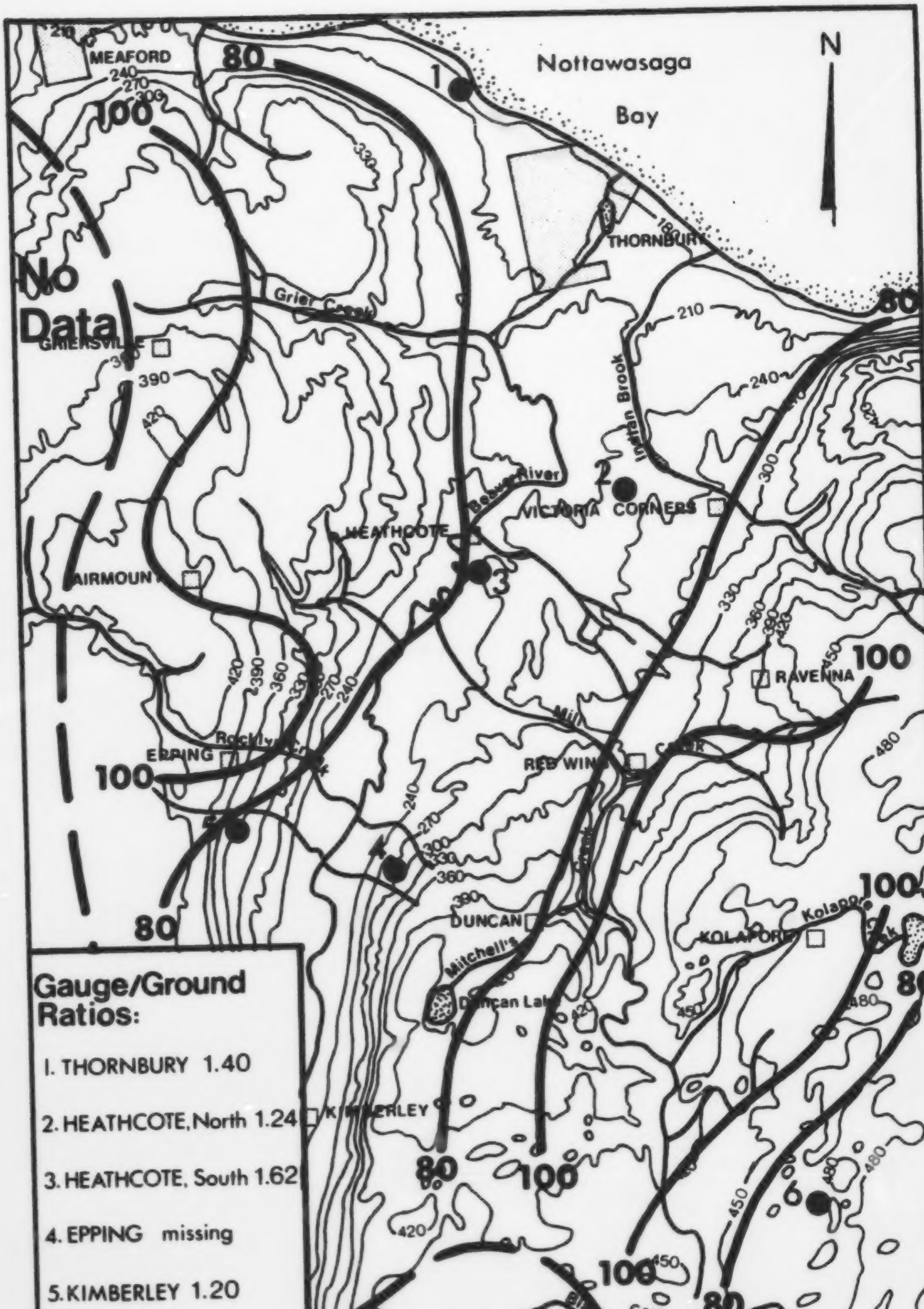
N
Nottawasaga
Bay
MEAFORD
THORNBURY
GRIERSVILLE
FAIRMOUNT
HEATHCOTE
VICTORIA CORNERS
EPPING
RED WING
RAVENNA
DUNCAN
KOLAPORE
KIMBERLEY
FEVERSHAM
Grier Creek
Beaver River
Indian Brook
Rocklyn Creek
Mill Creek
Kolapore Creek
Mitchell's
Duncan Lake
Eugenia Lake
Bighead's Creek
No Data
80
100
1
2
3
4
5
6
210
240
270
300
330
360
390
420
450
480
Gauge/Ground Ratios:
1. THORNBURY 1.40
2. HEATHCOTE, North 1.24
3. HEATHCOTE, South 1.62
4. EPPING missing
5. KIMBERLEY 1.20
6. FEVERSHAM 1.11

FIG. 11. Snow water equivalent (millimetres), December 30, 1984 to January 31, 1985.

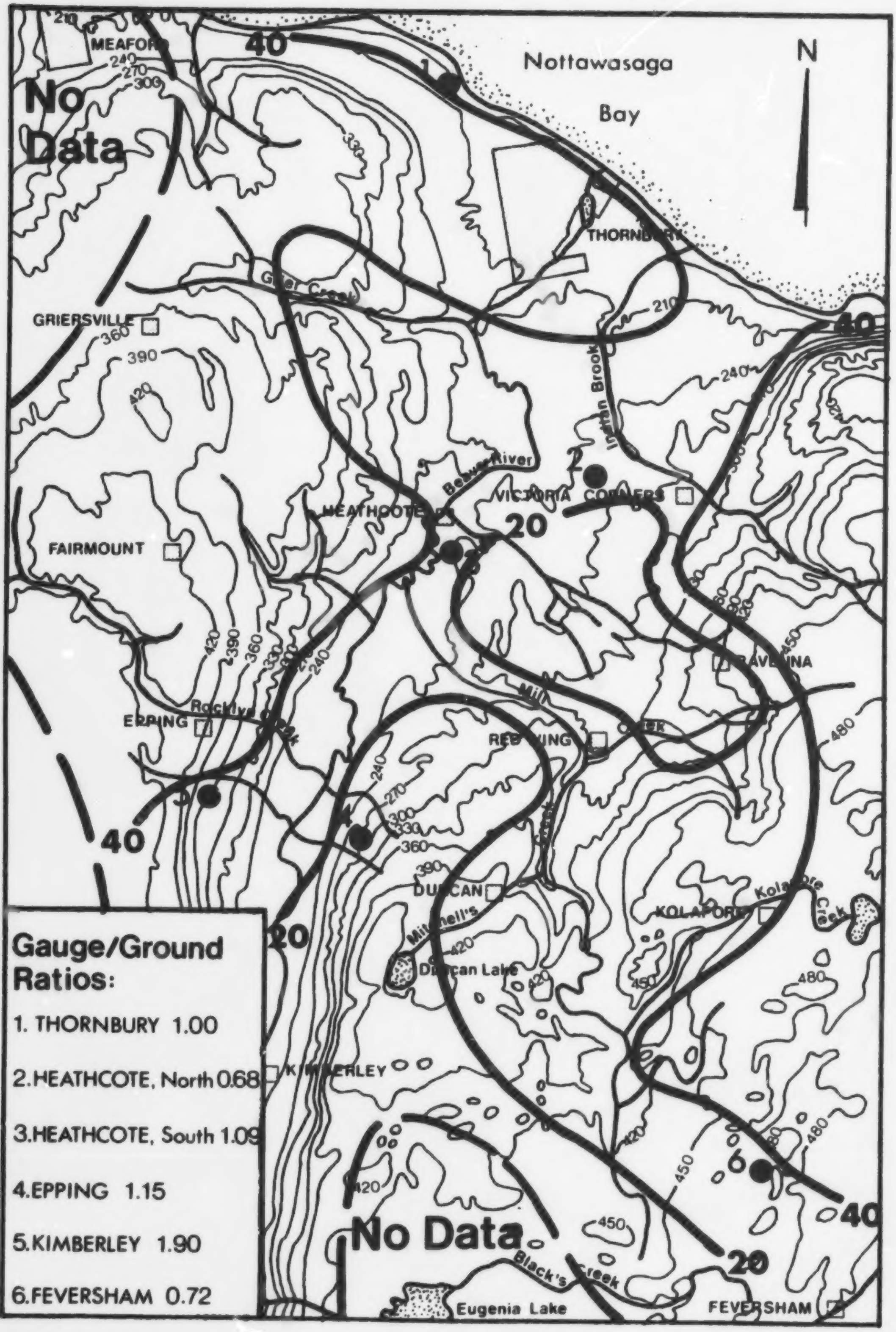
Nottawasaga
Bay
N
No
Data
MEAFORD
THORNBURY
GRIERSVILLE
FAIRMOUNT
HEATHCOTE
VICTORIA CORNERS
RAVENNA
EPPING
REDWING
DUNCAN
KOLAPORE
KIMBERLEY
FEVERSHAM
Eugenia Lake
Duncan Lake
Beaver River
Indian Brook
Grier Creek
Rocklyn Creek
Mill Creek
Mitchell's
Kolapore Creek
Black's Creek
No Data
40
20
1
2
3
4
5
6
210
240
270
300
330
360
390
420
450
480
Gauge/Ground Ratios:
1. THORNBURY 1.00
2.HEATHCOTE, North 0.68
3.HEATHCOTE, South 1.09
4.EPPING 1.15
5.KIMBERLEY 1.90
6.FEVERSHAM 0.72

FIG. 12. Snow water equivalent (millimetres), January 25, 1986 to February 11, 1986.

a somewhat arbitrary figure, to compensate for the fact that much of the winter snowfall along the shore is of the locally produced "lake effect" type, which has fine crystal structures and is very light. The densities of such snow are considerably less (0.05–0.08) than the national "standard" (0.10). At regular climatological stations like Thornbury Slama, the snowfall water equivalent is based on the depth of the freshly fallen snow, multiplied by 0.10.

An examination of the point precipitation values at the stations represented by snow on the ground indicates reasonably representative conditions regarding the surrounding areas at the lower elevations. However, the Feversham (plateau) and Epping (west slope) stations are sited about 2 km to the south of heavy precipitation zones. This latter pattern is confirmed in the second survey (Fig. 12), representing cumulative precipitation from January 25 to February 11, 1986. The period was characterized by strong winds from all quadrants, in the following sequence: SE, NW, NE, and SW.

Gauge to ground-snow ratios are seen to be quite different in this survey, being even, or slightly greater than one in the lakeshore, valley bottom, and west slope areas, and being less than one at the lake plain and plateau sites. The latter situation suggests that these are accumulation zones for wind-blown snow. A very distinctive scour zone occurs along the lower east slope and is well typified by the Kimberley station where the ratio is 1.9. The 20-mm isoline identifies this zone and it may be seen that the Heathcote North station (lake plain) is about 1 km to the north, just outside the area.

In summary, more surveys are required, but the major winter precipitation zones are generally evident. The network provides contributing information towards characterizing these zones, but some station relocation would improve this knowledge.

COMPONENTS FOR LAND CAPABILITY RATING

Light — The latitude of the Beaver Valley corresponds closely to the southern limit of the Huronian Life zone so that adequate light for all species is available unless blocked by topography. As Figure 13 indicates there is some topographic blocking of sunshine in the narrow valley section near Kimberley. This corresponds to 12% of the solar period on June 22 or 25% on December 22. This sheltering effect probably has no great significance for trees, but has been taken advantage of by ski resorts which are located on east-facing slopes to minimize snowmelt during late winter afternoons.

Heat — The seasonal energy available for plants declines inland with elevation. Accumulations of growing degree-days are reduced from 2032 (1951–80 normal) at Thornbury to 1732 at Redickville (44°14′N, 80°13′W, 526 m above sea level). It is commonly appreciated that there is a good

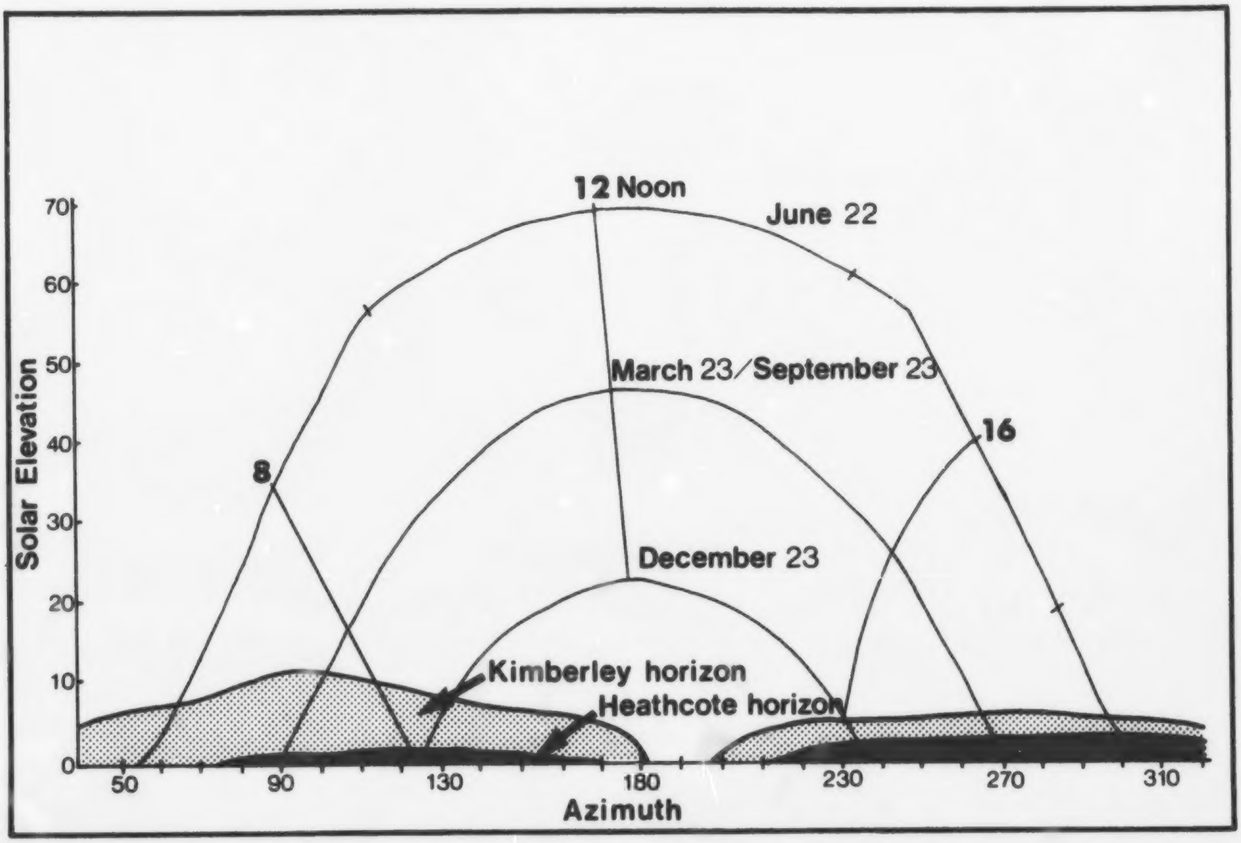

FIG. 13. Topographic blocking of sunshine at two Beaver Valley, Ontario, locations.

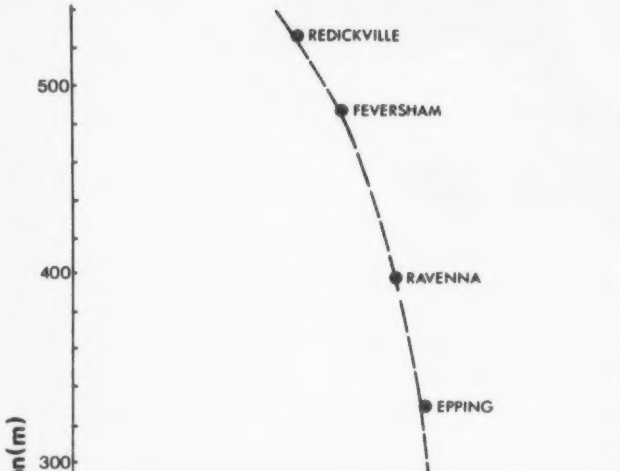

FIG. 14. Relationship between mean annual temperature and elevation in Beaver Valley, Ontario (GDD = growing degree-days).

relationship between the mean annual temperature and the accumulated growing degree-days at a point. Figure 14 shows the relationship between mean annual temperature and elevation in the Beaver Valley area. This does not appear linear from Thornbury to Redickville. It appears that the lake moderates the decline of temperature with elevation to about 350 m above sea level (above Ravenna), corresponding to 34 growing degree-days (GDD) reduction per 100-m rise. Above this, the decrease occurs progressively, averaging 184 GDD/100 m. The available heat for seedlings and other plants at particular localities may be determined from the daily station records and mobile surveys during critical synoptic events such as the radiation frost case. These meteorological data become critical if a vegetation response is foreseen.

Moisture — The measurements of precipitation at the topoclimate network suggest important local variability. The snow surveys confirm and amplify on these patterns. Throughout most of the year there is an adequate and at times more than adequate moisture supply for plants. However, in the summer months a deficit in available soil moisture is likely. Based on the work of Phillips (1976) who computed the monthly water balance for Canadian climatological stations using the Thornthwaite method, there is a seasonal deficit of near 100 mm at lower elevations near the lake reducing to less than 50 mm on the plateau.

The topoclimate network data suggest that the greatest seasonal soil moisture deficits may be greatest about 5 km up the valley from the lake where summer maximum temperatures are highest and precipitation is lower than at the lakeside and at higher elevations.

Conclusion

Much work remains to be done to refine and interpret the data being collected in the Beaver Valley, but at this stage some valuable information for land-use planning is available.

The topoclimate network, mobile temperature surveys, and snow surveys indicate discrete zones of heat and moisture accumulation during the year which may be integrated in plans to afforest parts of the area, or the techniques may be applied elsewhere. These and similar procedures are practical expedients to bring climate information to map scales suitable for planning which are used also for soil and other biophysical assessments.

Climate information used for site selection and development should be based on measurements where possible, although it is appreciated that there remains a high level of interpretation in deciding the validity and representativeness of the observations. Some biophysical assessments interpret climate from vegetation, soils and other natural indicators, but this should be considered a provisional recourse since the conjecture cannot be proven, and moreover, the natural indicators are suggesting the past, and not necessarily the present climate.

Finally, because of climate change, brought about by external forces, as well as the growth of the young trees, it becomes necessary to reassess the heat, moisture, and light available to the plantation from time to time.

Acknowledgments

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Intensive Forest Management: Is the Climate Right?

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Abstract

A more appropriate and less rhetorical question could be asked, is the technology right? Success in establishing the new forest depends greatly on the use of silviculture techniques that will result in a predictable growth response. New technologies for forest renewal may be either borrowed from other disciplines and geographic regions or developed locally from the best available scientific knowledge. The ability to predict response results from testing alternate techniques in statistically sound field trials. Data-based decision-making assumes greater importance with the increasing numbers of inputs associated with intensive forest management. Soils are the key to the data base for the choices of appropriate genetic stock, management system, and cultural practices.

Résumé

Une question plus juste et moins théorique serait la suivante: La technologie utilisée est-elle appropriée? Le succès de l'établissement de la nouvelle forêt dépend de l'emploi de techniques sylvicoles qui produisent une croissance prévisible. Les nouvelles technologies de régénération forestière peuvent provenir d'autres disciplines et régions géographiques ou être élaborées localement à partir des connaissances scientifiques de pointe. La capacité de prévoir une réponse découle de la mise à l'épreuve de techniques de rechange au cours d'essais statistiquement valables sur le terrain. Le processus décisionnel qui s'appuie sur l'acquisition de données augmente en valeur avec le nombre croissant d'entrées associées à une gestion forestière intensive. Les sols sont la clé de la base de données pour la sélection du matériel génétique, du système de gestion et des méthodes de culture appropriés.

Site Preparation Ecology: Some Climatic Connections

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Abstract

The performance of white spruce seedlings is used to demonstrate interrelationships between climate and site preparation in the boreal and subboreal spruce zones in British Columbia. Site preparation can alleviate low soil temperature, a major climatic constraint on successful forest renewal in these zones. The benefits of increasing soil temperature, however, may be nullified by interactions with other site factors such as fine soil texture and lack of nutrients in subsurface soil exposed by site preparation to increase soil temperature. Differences in snow depth between the boreal and subboreal zones can be another factor causing differences such as incidence of winter injury even when soil temperature has been increased. The performance differences presented show the need to recognize the connection between climate and site preparation and the interrelations possible with other factors.

Résumé

Le rendement des semis d'épinette blanche est utilisé pour démontrer les interrelations du climat et de la préparation du terrain dans les zones boréale et boréale inférieure d'épinettes en Colombie-Britannique. La préparation du terrain peut élever la basse température du sol, une contrainte climatique majeure qui entrave le reboisement forestier dans ces zones. Les avantages d'une hausse de la température du sol peuvent cependant être annulés par les interactions avec d'autres caractéristiques du terrain comme la texture fine du sol et le manque d'éléments nutritifs sous la surface du sol exposé lors de la préparation du terrain en vue d'augmenter sa température. Les écarts dans l'épaisseur de la couche de neige entre les zones boréale et boréale inférieure peuvent constituer un autre facteur à l'origine de variations dans la fréquence des dommages hivernaux, même lorsque la température a été élevée. Les écarts de rendement présentés démontrent combien il est nécessaire de prendre en considération le lien entre le climat et la préparation du terrain ainsi que les interrelations possibles avec d'autres facteurs.

Introduction

Low temperature is a major constraint to successful forest renewal in the boreal and subboreal spruce zones in British Columbia (McMinn 1985a,b). Some of the connections between site preparation and climate can be illustrated by examining the response of white spruce (*Picea glauca* (Moench) Voss) seedlings to temperature changes following site preparation. Time limitations preclude discussion of other climatic factors, such as water relations.

In northern forest zones, temperatures in undisturbed forest soils are below optimum for root growth (Dobbs and McMinn 1973). Removal of shading, competing vegetation, and the insulating blanket of surface organic matter (L, F, H horizons) to expose mineral soil can beneficially increase soil temperature (Dobbs and McMinn 1977).

The traditional method of controlling competing vegetation and of exposing mineral soil is bulldozer-blade scarification. Surface organic matter and the uppermost mineral soil layers containing the roots of competing vegetation are removed in strips and pushed aside.

These layers in boreal and subboreal forest soils, however, are the principal source of nitrogen for tree seedlings. Seedlings planted in subsurface mineral soil are initially deprived of this source of nitrogen and consequently may be chlorotic and slow growing.

In medium to moderately coarse-textured soils, enhanced root growth resulting from increased soil temperature following removal of competing vegetation and mineral soil exposure normally hastens access to the nitrogen in the surrounding superficial soil layers. Initial nitrogen deprivation, consequently, may not be of long duration. Root growth, however, is restricted in fine-textured (clay loam to clay) soils. In sites prepared by blade scarification, tree seedlings planted in exposed fine-textured, subsurface soils, therefore, may remain deprived of nitrogen for some years after planting despite increased soil temperature.

Immediate access to the nitrogen of surface organic matter improves the growth of planted tree seedlings when soil temperature is increased and competing vegetation is controlled (McMinn 1983). Covering inverted surface

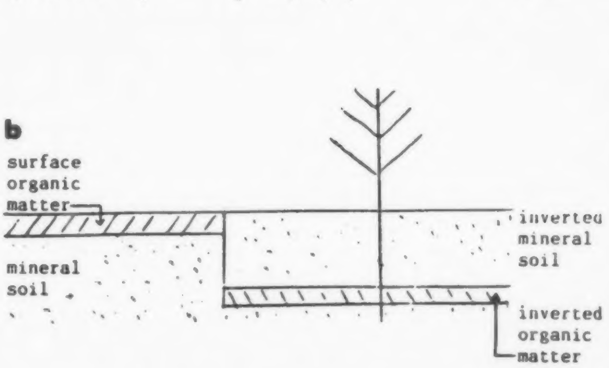

FIG. 1. Mineral soil covered inverted surface organic matter in the form of (a) inverted humus mound and (b) in situ inversion.

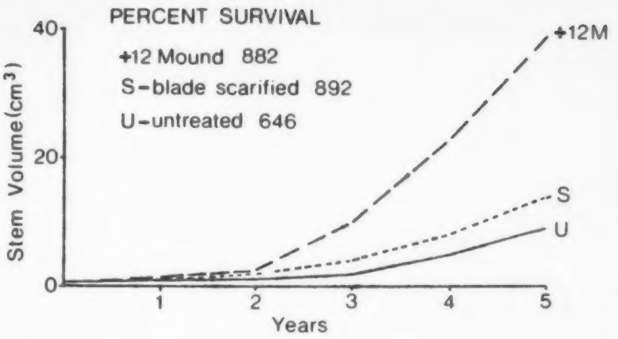

FIG. 2. Stem volume of 2 + 0 white spruce seedlings 5 yr after planting in an inverted humus mound with 12 cm of mineral soil capping (+ 12M), bare mineral soil exposed by blade scarification (S) and in untreated planting spots (U) in a moist, fertile white spruce site in the subboreal spruce zone.

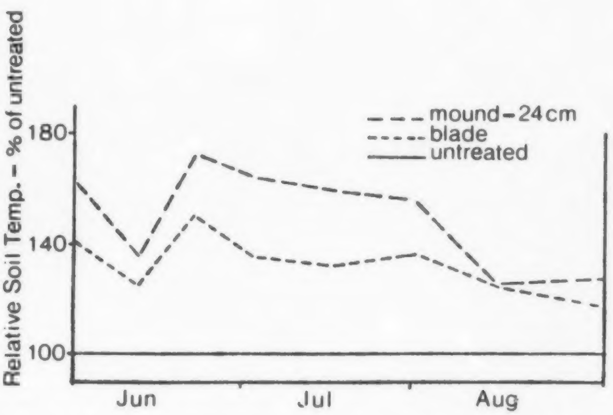

FIG. 3. Relative soil temperature 5 cm below the surface during the first growing season following blade scarification and inverted humus mounding (with 24 cm mineral soil cap) site preparation in a moist, fertile subboreal spruce zone site (Draper et al. 1985).

organic matter with a layer of mineral soil is a method of site preparation to achieve concommittant soil temperature increase, control of shading vegetation, and tree seedling access to surface organic matter. Such planting sites can be prepared as inverted humus mounds or as in situ inverted surface organic matter covered by mineral soil (Fig. 1). Inverted humus mounds can be machine prepared by the Bräcke Mounder and the Sinkkila. Land breaking plows produce furrow slices that are in situ inverted surface organic matter covered by mineral soil.

Comparable and contrasting results from trials with white spruce seedlings planted following various forms of site preparation are used to demonstrate site preparation and climatic interrelationships. Trials were conducted in the subboreal spruce zone east of Prince George and in the boreal black and white spruce zone near Dawson Creek, in the Peace River District of British Columbia.

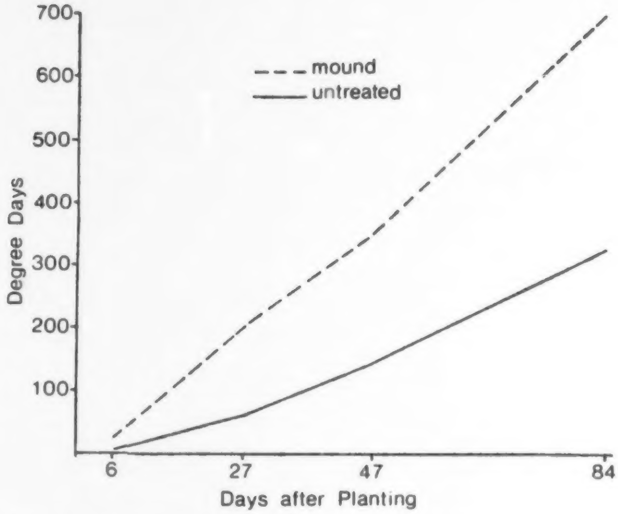

FIG. 4. Accumulated degree-days above a 5°C-threshold 10 cm below the soil surface in an inverted humus mound and in untreated soil in the subboreal spruce zone (Draper et al. 1985).

TABLE 1. Soil temperature, number and mass of roots, and foliage nitrogen content of white spruce seedlings after planting in prepared and untreated planting spots in moist, fertile, subboreal spruce zone sites in British Columbia.

Treatment	New roots[1] (> 10 mm long) 27 d after planting (no.)	Root mass[2] (< 1 mm diam.) 2 yr after planting (g)	Foliage nitrogen 1st yr (%)	Foliage nitrogen 2nd yr (%)	Temp. at 5 cm July: pm (°C)
Inverted humus mound	95	3.6a[3]	1.25	1.8	23
Blade scarified	—	1.9b	—	0.8	20
Untreated	15	0.7c	1.25	1.4	14

[1] Coal Mine Road (Draper et al. 1985).
[2] Stony Lake.
[3] Values in same column followed by different letter are significantly different ($P = .05$).

Subboreal Spruce Zone Trials

Seedlings in inverted humus mounds in a trial in the subboreal spruce zone had two to four times the stem volume of seedlings in untreated and blade scarified patches 5 yr after outplanting (Fig. 2). Soil temperature measurements 5 cm below the soil surface in another trial in the same zone (Draper et al. 1985) show relative temperature differences during the first growing season (Fig. 3). Mineral soil exposed by blade scarification or inverted humus mounding had considerably elevated temperatures compared with untreated soils. The differences resulted in increased accumulated degree-days above 5°C 10 cm below the soil surface (Fig. 4).

Increased numbers of new roots (Table 1) were formed in the warmer soil. Twenty-seven days after planting, white spruce seedlings in inverted humus mounds had 95 new roots longer than 1 cm compared with only 15 new roots in untreated sites (Draper et al. 1985). Such differences in root growth continued through the second growing season (Table 1). Seedlings in inverted humus mounds had 5 times the root mass of seedlings in untreated areas.

Although temperatures on a warm July afternoon in the blade scarified and inverted humus mound planting spots were comparable, the root mass of seedlings in mounds was nearly double that of seedlings in blade scarified patches. An explanation may lie in the differences in foliage nitrogen

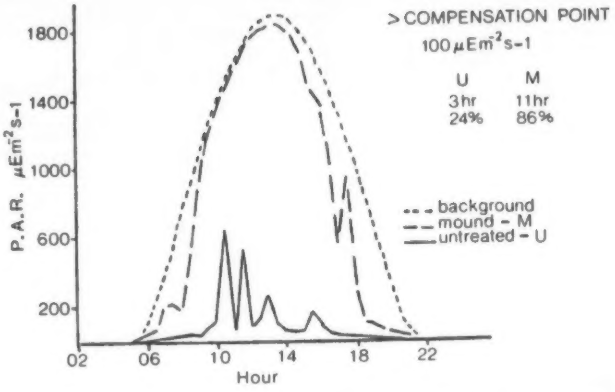

FIG. 5. Photosynthetically active radiation during a clear June day showing the large reduction beneath shading vegetation and the near background levels above an inverted humus mound in the subboreal spruce zone (Draper et al. 1985).

content of seedlings (Table 1). Excavation of root systems revealed numerous fine roots in contact with the inverted surface organic matter of mounds. Seedlings in scarified areas were not yet in contact with surface layers pushed aside, even 2 yr after planting. The cold soil of untreated areas seemed to result in relatively low nitrogen uptake despite roots being in contact with surface organic matter.

Regrowth of shading, competing vegetation on mounds, although greater than growth in scarified areas, was less than in untreated areas (Table 2) and appeared not to shade tree seedlings (Fig. 5). During the first growing season, the amount of photosynthetically active radiation during a clear day was close to background above inverted humus mounds (86%) but only 26% under the shade of vegetation in untreated spots.

Boreal Black and White Spruce Zone

In site preparation trials near Dawson Creek in the boreal spruce zone, results were both comparable and contrasting to those in the subboreal spruce zone east of Prince George. Soil temperatures were increased by plowing compared to shearblading (Table 3). Plowing covered the inverted surface organic matter with mineral soil which was exposed to warming by the sun. Shearblading removed woody vegetation, principally aspen (*Populus tremuloides* Michx.), but left the surface organic matter relatively undisturbed.

The increased stem volume of undamaged white spruce in the plowing treatment (Table 4) is comparable to the increased stem volume of seedlings in mounds in the subboreal spruce zone east of Prince George. Increased seedling growth is likely to reflect the increased soil temperature common to both zones when mineral soil is exposed.

A distinctive phenomenon in the boreal spruce zone near Dawson Creek was the frequency of winter damage. As many as 80% of seedlings (Table 5) were found to have been defoliated or killed by the end of the first winter after planting.

Desiccation of exposed tops when soils are still frozen is suspected to be a major factor in winter damage (Venn 1979). By contrast, only 30% of seedlings within a snow-fenced enclosure were winter damaged (Table 5). A striking difference in winter conditions affecting seedlings was the

TABLE 2. Regrowth of competing vegetation following various site treatments in a relatively moist, fertile subboreal spruce zone site near Stony Lake, British Columbia.

	2nd yr after planting (% cover)	3rd yr after planting (% cover)
Inverted humus mound	30a*	42a
Blade scarified	22b	19b
Untreated	57c	70c

*Values in each column differ significantly (P = .05).

TABLE 3. Soil temperature at various depths beneath the surface following plowing and no disturbance on the Stewart Lake Research Site, near Dawson Creek, British Columbia in the boreal spruce zone (30 July).

	Soil temperature	
Depth (cm)	Undisturbed (°C)	Plowed (°C)
5	11.5	18.5
15	10.7	17.2
20	10.1	14.5

TABLE 4. Stem volume of white spruce seedlings 2 yr after planting in plowed and undisturbed areas on the Stewart Lake Research Site, near Dawson Creek, British Columbia, in the boreal spruce zone.

Undisturbed (cm³)	Plowed (cm³)
1.2a*	2.7b

*Values significantly different (P = .05).

TABLE 5. Percentage of white spruce seedlings unaffected by winter damage following the first winter after planting in spring 1985 in fenced and unfenced areas on the Stewart Lake Research Site, near Dawson Creek, British Columbia, in the boreal spruce zone.

Unfenced (%)	Fenced (%)
20	70

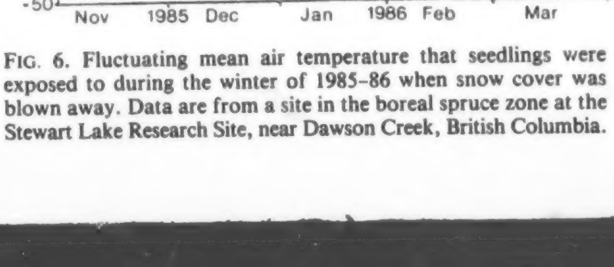

FIG. 6. Fluctuating mean air temperature that seedlings were exposed to during the winter of 1985–86 when snow cover was blown away. Data are from a site in the boreal spruce zone at the Stewart Lake Research Site, near Dawson Creek, British Columbia.

TABLE 6. Percentage of white spruce seedlings unaffected by winter damage following the first winter after planting in spring 1983 with and without fertilization at planting in undisturbed ground on the Stewart Lake Research Site, near Dawson Creek, British Columbia, in the boreal spruce zone.

Unfertilized (%)	Fertilized (%)
13	49

TABLE 7. Percentage of white spruce seedlings unaffected by winter damage following the first winter after planting in spring 1985 in plowed and undisturbed ground on the Stewart Lake Research Site, near Dawson Creek, British Columbia, in the boreal spruce zone.

Undisturbed (%)	Plowed (%)
22	40

periodic exposure of unfenced seedlings due to lack of snow cover. Fencing prevented the snow cover from being blown away from the enclosed seedlings and their exposure to alternating warm and cold periods (Fig. 6).

Winter observations in a subboreal spruce zone trial (Draper et al. 1985) showed that seedlings were continuously under the protection of the snowpack until spring. Soil and air temperature around tree seedlings remained essentially constant at 0°C and -4°C respectively.

Unfenced seedlings on the Stewart Lake Research Site near Dawson Creek which had been fertilized at the time of planting were less frequently winter damaged than unfertilized seedlings (Table 6). Also, fewer seedlings in a plowing treatment were winter damaged than seedlings in a shearblading treatment which left the soil surface essentially undisturbed (Table 7). Although foliage analyses are not yet available, it seems possible that nutrient levels in the plowing and fertilizing treatments were higher than in seedlings in undisturbed areas. Such a trend would be comparable to the increased nitrogen level in seedlings in inverted humus mounds in the subboreal spruce zone (Table 1) (Draper et al. 1985). These results are consistent with findings that suggest that increased nutrient content may reduce susceptibility to low temperature damage (Peschel 1982, Webb et al. 1983).

Discussion

Measurements in both the boreal and subboreal spruce zones in British Columbia show that there can be a correlation between climatic factors, such as soil temperature and seedling performance. Such correlation should form the basis for site preparation practice. Interacting factors, however, can negate the benefits of increased soil temperature. For example, seedlings planted in fine-textured subsurface soil exposed with the intent of improving soil temperature may not respond to increased soil temperature because root growth is inhibited in compact soil. Low nutrient availability in subsurface soil may also nullify the response of seedlings to temperature increase. Snow depth is another factor that may affect seedling performance even when soil temperature had been increased. Lack of snow cover in the boreal zone may expose seedlings to fluctuating winter temperatures and winter injury more frequently than in the subboreal zone where snow cover is generally deeper.

Although the results presented do not cover the full range of climatic connections, they clearly show the need to be cognizant of the correlation between climate and site preparation for forest renewal in the boreal and subboreal zones in British Columbia. Such correlations are also likely to be significant in other zones in other regions.

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Climatic Influences on Jack Pine and Black Spruce During Eight Growing Seasons Since Planting on a Dry and a Fresh Site in Northern Ontario

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Abstract

In 1979 black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.) bare-root nursery stock were planted on one dry and one fresh site in a cutover located north of Wawa, Ontario. The incidence of multiple leadering in black spruce on the fresh site was considerably greater than on the dry site, because on the fresh site the spruce had been damaged more severely by frost. After eight growing seasons the black spruce showed differences in volume but not in height between sites. Jack pine, on the other hand, suffered little to no externally visible frost injury on either side. Pines on the fresh site were significantly larger in both height and volume than on the dry site. Frost rings occurred in both species and on both sides, but with greater degrees of severity on the fresh site.

Résumé

En 1979, du matériel de reproduction à racines nues d'épinette noire (*Picea mariana* (Mill.) B.S.P.) et de pin gris (*Pinus banksiana* Lamb.) de pépinière a été planté sur un terrain sec et un terrain vert dans une zone coupée à blanc située au nord de Wawa, en Ontario. On a noté une apparition beaucoup plus importante de flèches multiples sur l'épinette noire établie dans le terrain vert que sur ce même conifère dans le terrain sec en raison des dommages plus graves causés par la gelée à l'épinette du terrain vert. Après huit saisons de croissance, l'épinette noire a montré des différences de volume mais non de hauteur entre les terrains. Par contre, le pin gris n'a subi que peu ou pas de dommages externes causés par la gelée sur les deux terrains. La hauteur et le volume des pins du terrain vert étaient bien supérieurs à ceux des pins du terrain sec. Bien que des cernes de gelée soient apparus chez les deux espèces sur les deux terrains, ceux des arbres du terrain vert étaient plus graves.

Introduction

Forest sites can differ greatly in productivity due to differences in soil nutrients, moisture, and texture as well as climatic factors. It is difficult to examine these factors in isolation, but in our ever-expanding regeneration effort it becomes increasingly more important to understand the tree–site interrelationship. We should know what species and stock type to plant on a specific site. We should be able to predict when the planted trees reach the "free-to-grow" stage and how much the trees will grow annually. To acquire this knowledge, many species, stock type, and site comparison studies need to be conducted in climatically separate areas.

Therefore, we conducted an outplanting trial in a northern Ontario cutover with 2+0 jack pine (*Pinus banksiana* Lamb.) and 1.5 + 1.5 black spruce (*Picea mariana* (Mill.) B.S.P.) on two adjacent sites (one dry and one fresh), which differed mainly in soil moisture and microclimate. The results of this trial, eight growing seasons after outplanting, are discussed in this paper.

Materials and Methods

The cutover was located in Makawa Township (lat. 48°36′N, long. 83°55′) about 80 km north of Wawa, Ontario. The original stand consisted of approximately 80% jack pine and 20% poplar (*Populus* spp.) on the dry (upland) site and 40% jack pine and 60% black spruce on the fresh (lowland) site. The area was logged in 1977, prescribed burned, and TTS disc trenched in the spring and summer of 1978. The dry site and fresh site have a 1 and 3 moisture regime, respectively (Hills 1960, Jones et al. 1983). The soils are stone free, fine to medium sand, shallow to deep over bedrock, with pH ranging from 5.1 to 5.4 on the dry site and 4.7 to 5.2 on the fresh site. The trees were planted in a randomized block design with 35 trees per replication, and five replications. Both sites were planted with 2+0 jack pine and 1.5 + 1.5 black spruce on May 31, 1979. Survival, annual height increment and total heights were measured for the first 5 yr after outplanting and then in the 8th yr. After eight growing seasons four trees/species/site were selected on the basis of plot means of height and diameter at breast height, and cut for growth layer analyses. From each tree, discs were cut at ground level and at 15-cm intervals to the top of the tree. The width of annual growth layers was measured along two radii of each disc, using "TRIM" (Tree Ring Increment Measuring system) growth layer analysis procedures, as described by Fayle and MacIver (1986). Total height and survival (after arc sine transformation) were subjected to analysis of variance, with the results tested at the 95% confidence level.

Results and Discussion

After eight growing seasons, the survival of jack pine was 77 and 70%, while for black spruce it was 89 and 82% on the dry and fresh site, respectively. These differences were significant at the 5% level. The lower survival on the fresh site resulted partially from water ponding at planting time, which hampered initial establishment in the first 2 yr after planting.

Total height on the dry and fresh site differed significantly for jack pine but not for spruce (Fig. 1). Since the fresh site is more productive, the somewhat lower black spruce heights were unexpected. However, on the fresh site greater numbers of new spruce leader growth were killed every year by spring frosts than on the dry site, thus negating height differences due to site productivity.

The results of the growth layer analyses on the destructively sampled trees show that the cumulative volumes for both species were significantly better on the fresh site than on the dry site (Fig. 2), noticeably so by the 4th yr. Jack

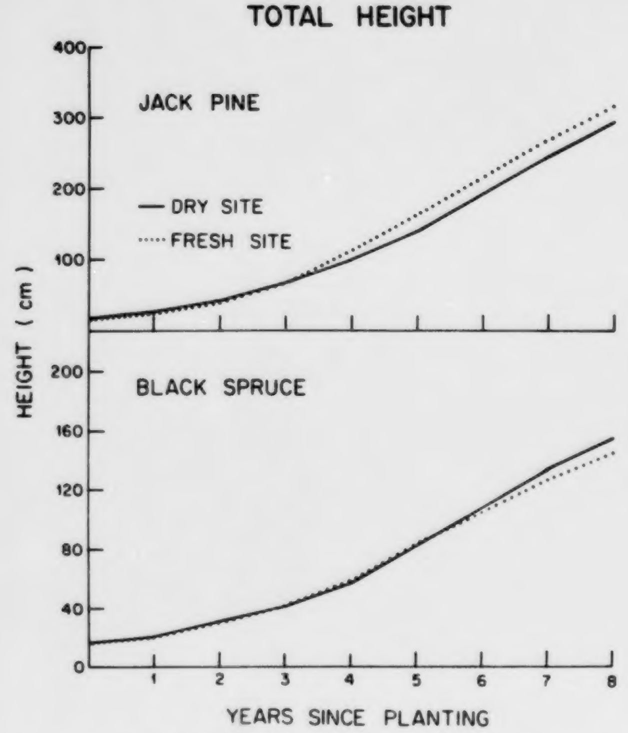

FIG. 1. Total height of jack pine and black spruce 8 yr after outplanting on a dry and fresh site. The height difference for jack pine is significant at the 5% level, but nonsignificant for black spruce. Note the difference in height scale between spruce and pine.

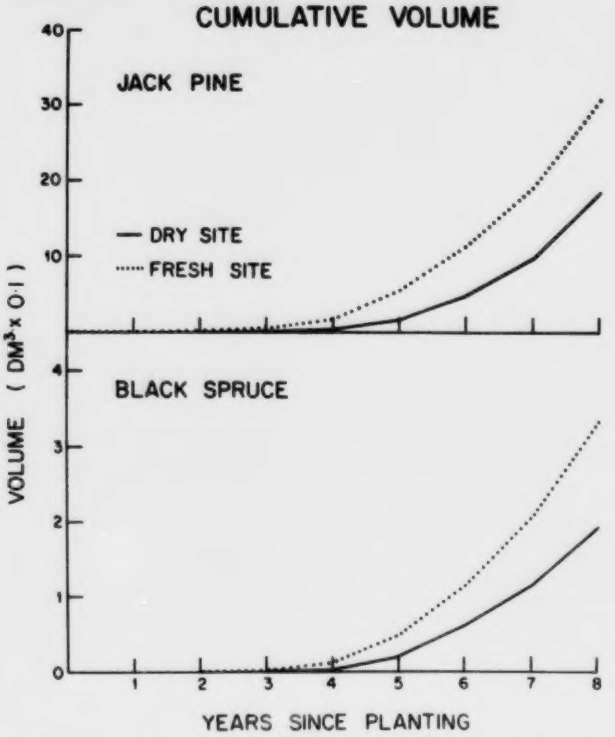

FIG. 2. Cumulative volume of jack pine and black spruce 8 yr after outplanting on a dry and fresh site. The volume was calculated from four representative trees/species from each site using "TRIM." Note difference in volume scale between spruce and pine.

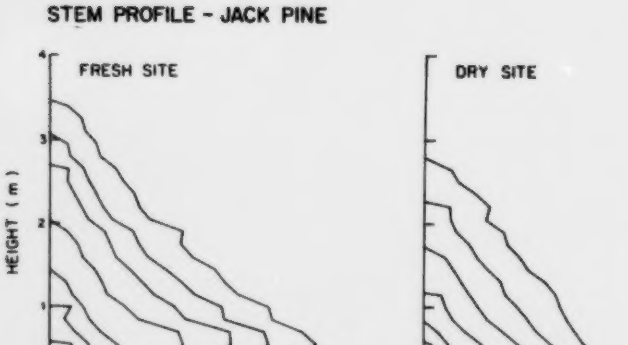

FIG. 3. Stem profile of a typical jack pine, one from a fresh site and one from a dry site. Note the differences in annual growth layer width between the fresh and dry site.

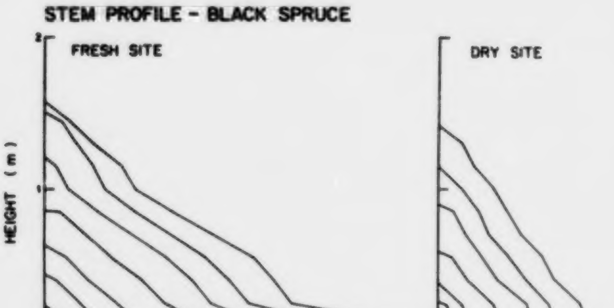

FIG. 4. Stem profile of a typical black spruce, one from a fresh site and one from a dry site. Note the difference in annual growth layer width between the fresh and dry site.

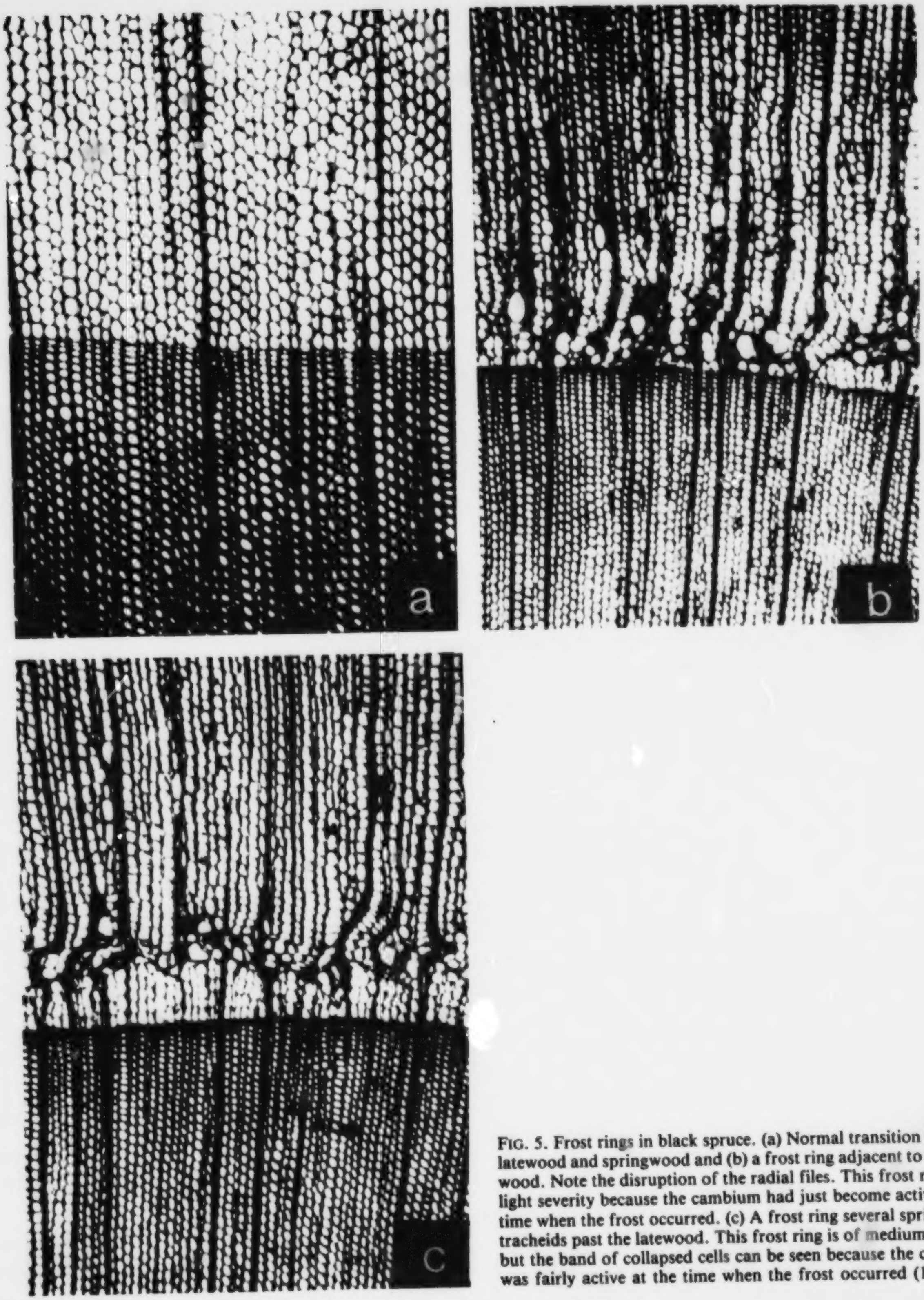

FIG. 5. Frost rings in black spruce. (a) Normal transition between latewood and springwood and (b) a frost ring adjacent to the latewood. Note the disruption of the radial files. This frost ring is of light severity because the cambium had just become active at the time when the frost occurred. (c) A frost ring several springwood tracheids past the latewood. This frost ring is of medium severity but the band of collapsed cells can be seen because the cambium was fairly active at the time when the frost occurred (120×).

pine cumulative volume is nearly ten times greater than that of spruce.

The reason for these volume differences becomes readily apparent when the stem profiles for both species and sites are examined (Figs 3 and 4). The ring widths (i.e., diameter growth) on the fresh site are considerably greater for both species than those on the dry site even shortly after planting.

Although jack pine total height showed differences in site productivity, cumulative volume and ring width appear to be more reliable indicators of productivity on frost prone sites for both species than height.

The similarity of black spruce total heights on both sites was due to microclimatic differences between the sites. Spring frosts on the fresh site were more severe than those on the dry site, which resulted in more terminal leaders and laterals of black spruce killed on the fresh site. This caused greater loss of terminal dominance with considerable multiple-leadered "stem-form" on the fresh site, while the single "stem-form" prevailed on the dry site. On the other hand, jack pine terminal leaders were rarely killed by frost on either site, and therefore retained their terminal dominance and their single "stem-form."

The annual growth layers of both species were examined microscopically for frost rings using specially prepared slides (Glerum 1975). Frost rings of varying severity occurred in all annual growth layers of both species with the exception of the 1983 growth layer (Fig. 5). One of the most severe frost occurrences as documented by frost rings occurred in the 1986 growth layer. These frost rings were directly linked to a frost on June 17, 1986. These rings demonstrated that the frosts on the fresh sites were more severe than on the dry sites, although frost frequency was similar on both sites.

Although jack pine lost no measurable leader growth due to frost, as did black spruce, it had just as many frost rings as black spruce. This suggests that differential frost hardiness (Glerum 1985) among actively dividing cambial cells, phloem, and other cortical cells is greater in jack pine than in black spruce.

In several jack pine annual growth layers there was evidence that the last tracheids in the latewood had not fully lignified. This lack of lignification is attributed to the effect of early fall frosts on tracheids, which in their final stages of maturation (i.e., lignification) are the most sensitive to the dehydrating effect of frost (Glerum and Farrar 1966). This type of under lignification was never observed in black spruce. Lignification is the final phase of tracheid maturation and cambial activity and apparently occurs later in the season (i.e., late summer–early fall) with the genus *Pinus* than with the genus *Picea*. We suggest, therefore, that this could be one reason why spruces occur at the tree line but not pines.

The frost damage observed in the form of frost rings clearly shows the importance of climatic selection in the planting site and the effect of climatic factors on tree growth. Loss of wood volume must occur. However, at this time, it is difficult to estimate how much wood volume is lost due to climatic stresses but judging from the occurrence of frost rings and the lost leader growth in spruce it may be considerable.

Conclusions

Black spruce height growth was significantly reduced by frequent spring frosts on the fresh site compared with the dry site. No significant reduction in height growth due to frost occurred in jack pine. On frost sensitive sites, total volume is a better indicator of site productivity for both jack pine and black spruce than height, particularly for spruce. The fresh site is clearly more productive than the dry site. Actively dividing cambial cells of both species are equally sensitive to frost. However, in spruce the phloem and cortical cells are less frost hardy than in pine, resulting in the loss of actively growing leaders in spruce but not in pine.

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Role of Seasonal Snow Cover in Forest Regeneration

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Abstract

The sequential development of the seasonal snow cover and its effects on seedlings and trees are discussed. Physical properties of the snow cover, their direct and indirect relevance to the survival of forest plants, and their significance to the supranivean, intranivean, and subnivean microclimates are described.

Two main cases of snow cover development are treated: (1) snow cover in forested terrain where there is little or no influence of wind and (2) snow cover in open terrain where the influence of wind is strong. Each influences forest regeneration differently. The multifaceted role of the snow cover in plant life and its multiple linkages to climate are emphasized.

Résumé

L'exposé porte sur l'évolution séquentielle de la couche nivale saisonnière et ses effets sur les jeunes plants et les arbres. On examine les propriétés physiques de la couverture neigeuse, leurs effets directs et indirects sur la survie des plantes forestières ainsi que leur importance pour le microclimat supranivéen, intranivéen et subnivéen.

Deux exemples majeurs de couche nivale sont traités: l'enneignement des terrains forestiers où l'effet du vent est nul ou minime et l'enneigement d'un terrain à découvert où soufflent des vents forts. Dans chaque cas, l'effet sur la régénération forestière est différent. On fait ressortir les multiples aspects du rôle de la couverture neigeuse dans la vie végétale et ses nombreux liens avec le climat.

Introduction

Snow is a climate-related factor of considerable economic importance that not only affects forestry operations but also influences forest plants throughout their life cycle. Snow is both a product of climate and a climate controller and its effects on trees and seedlings are multifaceted. The purpose of this paper is to elucidate some of the mechanisms by which snow influences forest regeneration.

Snow crystals are created in a process that reduces radiative heat losses from the ground surface and allows the atmosphere to lose heat in large quantities while maintaining a constant, fairly high temperature. Because of their very large specific surface area they form a snow cover that is a very efficient thermal insulator. The large specific surface area also ensures that snow crystals are efficient scavengers of gases and particulates on their way to the ground.

Partly as a result of its low thermal conductivity the snow cover sets up a microclimate at the snow/ground interface that is entirely different from that at the snow/air interface. Because of the thermal buffering capacity of the underlying soil and the heat flow from below, the ground/snow interface exhibits a steady, relatively warm temperature which in forested regions is usually within a few degrees below the freezing point. Local variations occur as a result of variations in snow depth. As a rule, the shallower the snow, the closer the interface temperature follows the air temperature. Therefore, in areas with mean annual air temperatures below 0°C permafrost tends to form in terrain locations where the snow cover is very shallow throughout the winter.

The ground has a much greater volumetric heat capacity than the snow cover and also in most cases has a thermal conductivity that greatly exceeds that of the snow cover. As a result of the difference in thermal conductivity between the snow cover and the underlying ground there is a discontinuity in the vapor pressure gradient at the snow/ground interface. This causes desiccation of the near-surface layers of the soil during the winter.

Heat transfer through the snow cover is not a simple conduction procedure. It is a process where both moisture and heat are transferred by conduction in the ice matrix and by conduction and evaporation–sublimation across the interstitial air spaces. In addition, free and forced convection cause large temporal and spatial variations in the effective thermal conductivity of the snow cover.

At night, the steep density gradient of the air causes cold air to dribble into the snow cover as descending convective currents that follow least-resistance routes. It has been shown theoretically that uphill flows of warm air occur in the porous lower layers of snow on slopes. Flows of air also occur in these layers in response to spatial variations in the surface pressure field created by obstacles to the air flow. In daytime, spatial variations in the surface air pressure field cause pumping of air in the near-surface layer (Granberg 1981). These air movements cause rapid variations in the temperature of the surface layers of the snow cover (Fig. 1).

Because of its blackbody properties and its low thermal conductivity, the snow cover strongly influences the supranivean microclimate which in clear-sky conditions is characterized by a stable nocturnal air stratification with often very steep temperature gradients. At Schefferville, Quebec, it is not uncommon to find snow surface temperatures that are 5°–10°C colder than the air temperature at screen level (Granberg 1981, Bartoshesky 1983). The surface temperature tends toward an equilibrium with the radiative temperature of the sky which in clear-sky conditions may be typically −70°C. It does not reach that equilibrium, however, because heat is transferred to the surface of the snow cover from the air. The moisture transfer makes the snow surface change character in response to the radiative heat loss characteristics. It is presently not known whether or not these changes may alter the emissivity of the snow surface which in the literature is often assumed to be close to unity. Values as low as 0.83 have been reported in the literature (Sellers 1965).

Ice is transparent in the visible range of the electromagnetic spectrum but because of the multiple reflections and refractions at the many air/ice interfaces, a fresh snow cover

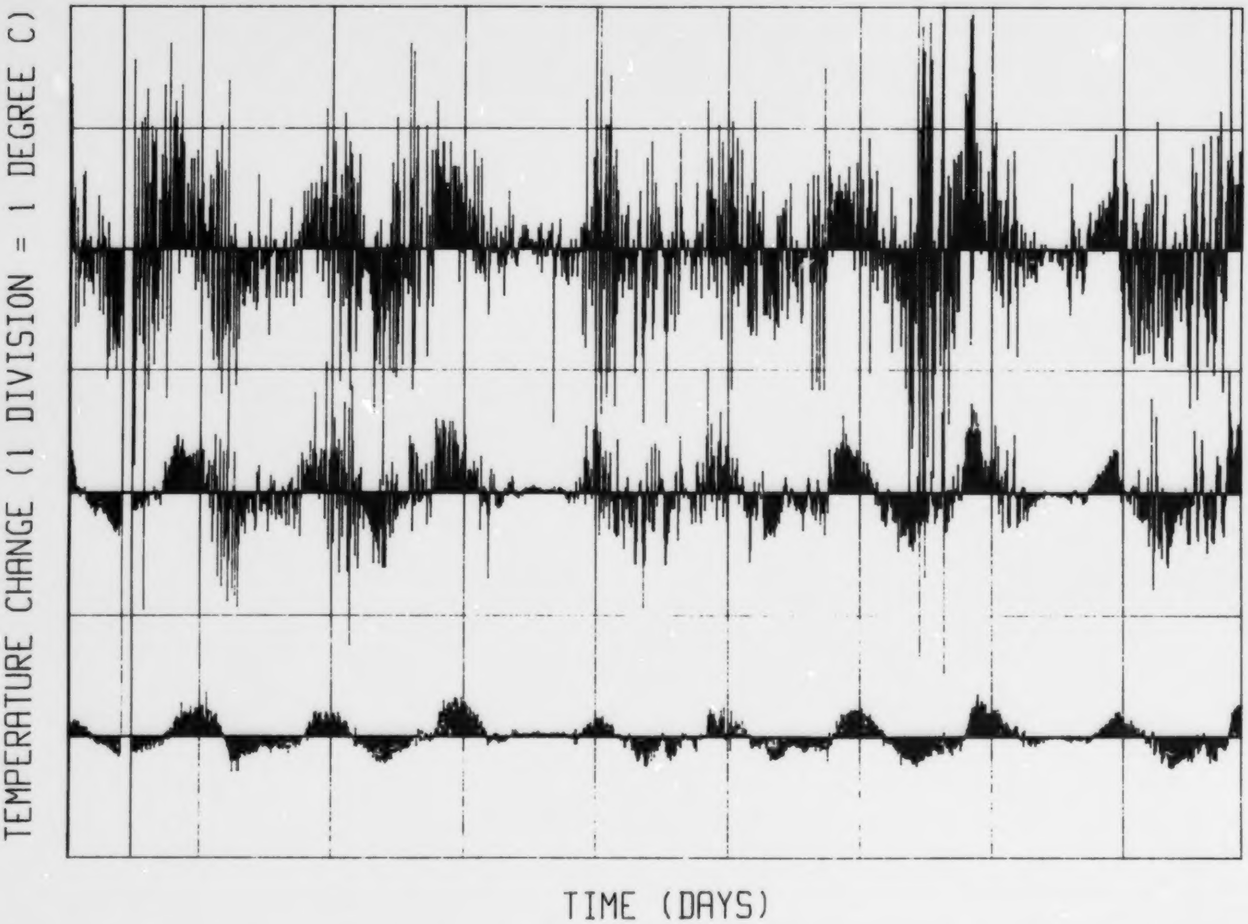

FIG. 1. Measured snow temperature changes over 10-min intervals at the snow surface (*top*), 5 cm (*middle*) and 10 cm (*bottom*) below the snow surface.

has a very high albedo. The transparency of ice allows solar radiation to be transmitted deep into the snow cover (Fig. 2). Its deepest penetration is for wavelengths around 580 nm (Kulkarni 1986) and the depth of penetration varies seasonally, both as a result of variations in available radiation and as a result of changes in the snowpack structure. In spring, the penetration of solar radiation increases as a result of increasing grain size (Kulkarni 1986). Penetration of solar radiation allows nocturnal heat losses to be recovered through internal absorption of solar radiation rather than by conductive processes.

Snow is permeable but its permeability to air and water is highly variable. In a typical snow cover the air permeability may be 500 times greater at the ground/snow interface than at the air/snow interface. This gives the snow cover a tendency to trap gases released by soil organisms. The air in the snow cover is therefore usually enriched in carbon dioxide. During snow drift transport the snow crystals drifting along the surface are fragmented into small splinters which produce a snow deposit of very low air permeability, compared with snow that accumulated in the absence of wind. This provides a fairly impermeable surface layer in open terrain and, in effect, gives a negative feedback to wind-induced ventilation.

The snow cover is a laminated deposit of snow layers, each of which formed under a wide variety of atmospheric conditions and was deposited in different thicknesses. Depending on time of year and location, partial or full melting of the layer may occur and liquid and freezing precipitation may from time to time be added to the snow cover. Ice, even at low winter temperatures, is close to the triple point of water and thus quite unstable. A snow cover therefore is in a continual state of change. These changes are referred to as snow metamorphism (Bader et al. 1939, Eugster 1952, Colbeck 1983). Snow metamorphism proceeds in different directions and at different rates depending on environmental conditions.

One very important environmental factor is wind. In this paper we will examine snow cover development in wind-sheltered and wind-exposed environments, respectively. From a forestry viewpoint this subdivision is appropriate since clearcutting of large tracts of forest often transforms a wind-sheltered environment into a wind-exposed one. The associated differences in snow conditions may be of considerable significance to the success of reforestation attempts.

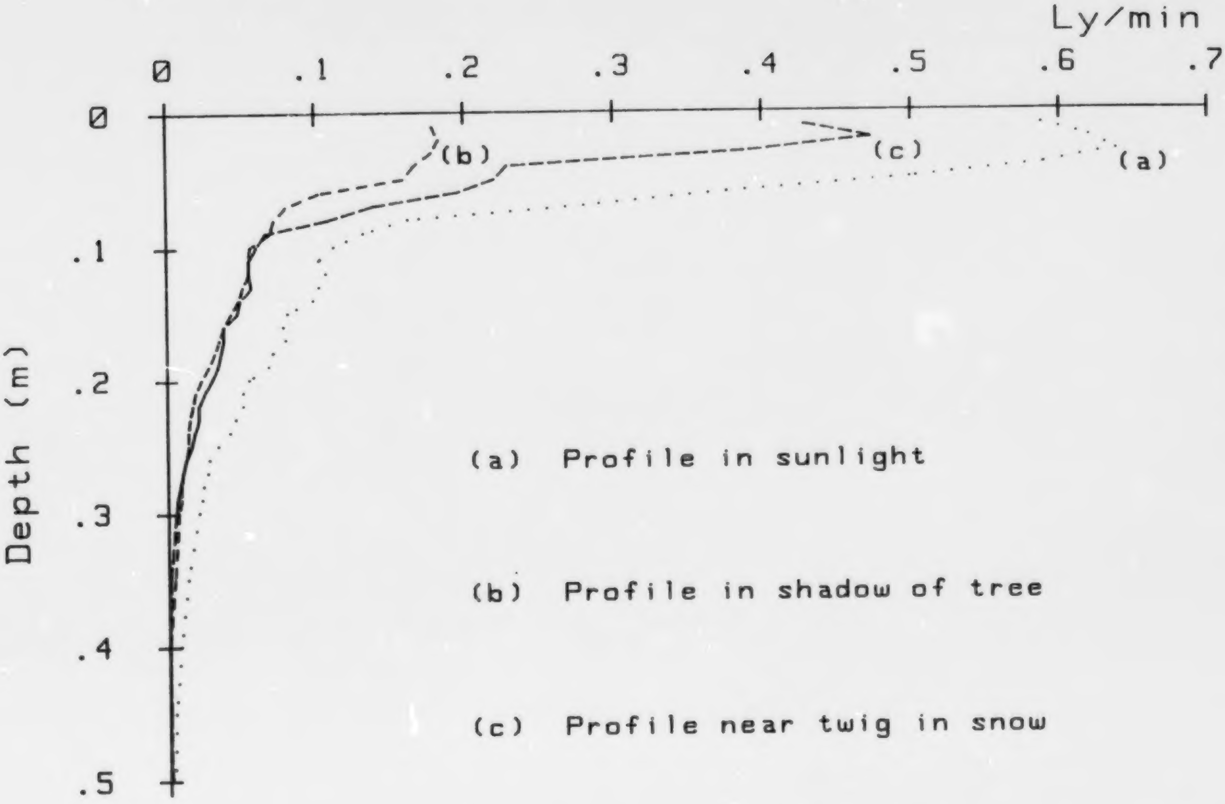

FIG. 2. Penetration of panchromatic solar radiation in snow at Schefferville.

Wind-Sheltered Snow Covers

In the absence of wind each layer in the snow cover is spatially more or less uniform, if we exclude interception effects. Local variations in snowfall intensity may cause additional variations and elevational differences may force variations in the solid/liquid precipitation ratios and in the amount of deposited snow.

Depending on storm frequency, each layer spends a shorter or longer time as surface deposit. It is in this position that the layer is most strongly exposed to the influences of weather factors and it is in this position that the layer undergoes the most rapid changes. The newly deposited snow initially has a very large specific surface area as a result of its dynamic growth environment. Once the crystal comes to rest in the snow cover, however, this large specific surface area is no longer tenable. Under the influence of rapid temperature fluctuations, air movements, and effects of surface curvature, moisture is transferred, via the vapor phase, from sharply convex to sharply concave parts of the ice skeleton. This process is known as destructive metamorphism, referring to the rapid destruction of the intricate shapes of the atmospheric snow crystals. It leads to a general rounding and a fairly rapid densification of the newly deposited snow.

The snow cover gradually settles under its own weight. Ice under sustained stress deforms quite readily and the bonds between different grains therefore adjust to stress concentrations, leading to a gradual increase in snow density. A snow cover, because of this ongoing densification, moves downward in the solid state. This would soon lead to a very dense snow cover were it not for the fact that the downward movement is balanced by an upward mass movement in the vapor phase, driven by the temperature/vapor pressure gradient. The upward mass movement leads to a recrystallization of the ice skeleton which results in a general coarsening of snow grains and a reduction in the total number of intergranular bonds per unit volume. This process, which is referred to as constructive metamorphism (Bader et al. 1939) or temperature gradient metamorphism (Sommerfeld and LaChapelle 1970), leads to the formation of the depth hoar layer which is porous and of high air permeability. Small mammals can easily burrow through the snow in this layer. However, the upward vapor flow often leads to a weakening of the lower strata which may collapse, causing periodic, near-instant lowerings of the snow cover by several centimeters. In steeply sloping terrain, an avalanche may be triggered by this process. To intranivean plants, the associated sudden increase in strain rate may cause structural failure.

The snow cover densifies rapidly during melt. The increased local heat exchange in wet snow leads to a rapid increase in grain size and a general rounding of snow grains (Colbeck 1973). The increased grain size allows a deeper penetration of solar radiation (Kulkarni 1986). When the snow is wet, the effective optical grain size is increased, further increasing the penetration of solar radiation. There is also an increase in density and effective optical grain size due to refreezing of meltwater within the snow cover. When the ground is below freezing a layer of high density snow-ice forms at the snow/ground interface as a result of such refreezing. Similarly, in the early stages of melt, existing ice crusts and layers of low permeability in the snow cover tend to be enhanced by intercepted meltwater dribbles which refreeze.

Wind-Exposed Snow Covers

Under the influence of wind newly deposited snow is easily eroded and redistributed (except at melting and near-melting temperatures). The new layer of snow deposited by each storm therefore varies spatially both in thickness and in other properties. Total snow transport varies approximately as the cube of the near-surface wind speed (Komarov 1954). Under most natural conditions more than 90% of the total drift transport takes place in a layer 0–10 cm above the surface. The snow particles roll or skip along the surface or move by saltation in a series of short jumps. Only a small portion of the smallest particles are carried to greater heights by updrafts in the boundary layer (Budd 1966, Budd et al. 1966).

The mode of snow transport has two important consequences. In addition to the fragmenting of snow grains and its effects on density and air permeability, wind redistributes the snow from areas of high to areas of lower wind stress. The wind stress at the surface changes according to topography and vegetation roughness. It is the erosion rate that is affected by the variations in wind stress; the deposition rate is merely a function of the amount of airborne snow, its vertical distribution, and its settling velocity. As most of the snow is transported very close to the ground surface, minor local variations in wind stress lead to major variations in net accumulation rates. This feedback effect is the cause of the familiar airfoil shape of snow drifts. The snow tends to accumulate so as to form a least-resistance surface, that is, one that minimizes velocity variations in the air flowing past it.

In open terrain, snow drift transport leads to a snow accumulation sequence which is controlled by snowfall, wind patterns, and surface roughness. Snow accumulation changes the aerodynamic roughness of terrain by burying microroughness elements such as brush vegetation and by filling in minor concavities of the terrain. Therefore, with an increasing total amount of snow on the ground, near-surface wind speed and therefore drift transport also increase as a result of the gradual elimination of surface roughness.

Broadly, the accumulation sequence in open terrain may be described as follows: During the first snowfall relatively little snow drifting takes place because of the overall rough microstructure of the ground. The wind transport that does occur mainly consists of snow drifting off particularly smooth portions of the terrain, such as road surfaces, to their leeward sides where drifting snow is immediately trapped by the rough microstructure of the terrain. This leads to a downwind extension of the smooth areas. Over the next few storms, the smooth areas expand. Little or no snow is retained on them; most of the new snow drifts off them and collects at their downwind edges. Meanwhile, snow accumulation gradually inundates the rough microstructure of the ground, initiating new smooth areas while neighboring smooth areas begin to merge. With each merger the snow grains begin to travel over longer distances and the snow accumulation patterns become increasingly controlled by decreasing spatial variations in surface wind stress. Accordingly, there is a more gradual variation in the thickness of snow layers deposited by individual storms. The deepest accumulations now occur on lee slopes and in local topographic lows while ridge crests still remain largely snow-free. The steeply dipping strata, characteristic of the deposits at the downwind edges of the smooth area, are buried by snow deposits which exhibit a subhorizontal stratification with considerable local variations in the thickness from ridge crest to valley bottom. As a result of the increased drift transport distance, the deposited snow consists of finer fragments and is therefore denser than before the smooth areas merged. Oversnow travel for man and mammals becomes easier as the hardness of the surface layers, and thereby their ability to support loads, increase.

The spatial differentiation in snow depth that is eventually attained is controlled by the local topography and vegetation roughness, the amount of snowfall, the local windiness, and the general susceptibility of the snow to wind erosion. Figure 3 shows an example of the spatial differentiation in snow depth at Schefferville in later winter 1969. The figure shows snow depth variations measured in traverse surveys through different vegetation cover types ranging from alpine tundra (1) through recent burn (2), regenerating burn with trees 1–3 m tall (3), open woodland (crown closure < 30%) (4), and closed woodland (crown closure > 30%) (5).

Ice crusts form on the snow surface as a result of surface melt, liquid precipitation, rime deposition, and sublimation effects. As a rule, they are much more prominent in open than in forested terrain. In forested terrain trees intercept much of the rime and the freezing precipitation. In open terrain most crusts vary in thickness depending on topographic position and wind direction. Crusts created by sublimation processes are usually limited to open terrain where the necessary wind speeds occur. Melt crusts are also better developed in open than in forested terrain.

The melt sequence in open terrain differs considerably from that in forested terrain as a direct result of differences in the spatial variations in the water equivalent of the snow cover. In open terrain, areas of shallow snow in convex parts of the terrain become snow-free early in the melt season, often well before any snowmelt runoff occurs. On the other hand, the deep portions of the snow cover may persist well into the summer season with obvious detrimental effects on seedling establishment. In forested terrain the snow cover melts first beneath trees and the snow cover in the openings between trees disappears fairly uniformly, often several weeks in advance of the disappearance of the deep snow accumulations at forest edges and in open terrain.

Effects of Snow on Forest Regeneration

If we ignore the large-scale effects of the snow cover on earth's climate, we may coarsely group the effects of snow on forest regeneration into: (1) thermal effects, (2) moisture control, (3) transport/ trafficability effects, (4) growing season control, (5) mechanical effects, and (6) chemical effects.

THERMAL EFFECTS

Among beneficial effects of the snow cover on plants are thermal amelioration of the vegetation layers within the snowpack, protection of root systems from extreme low tem-

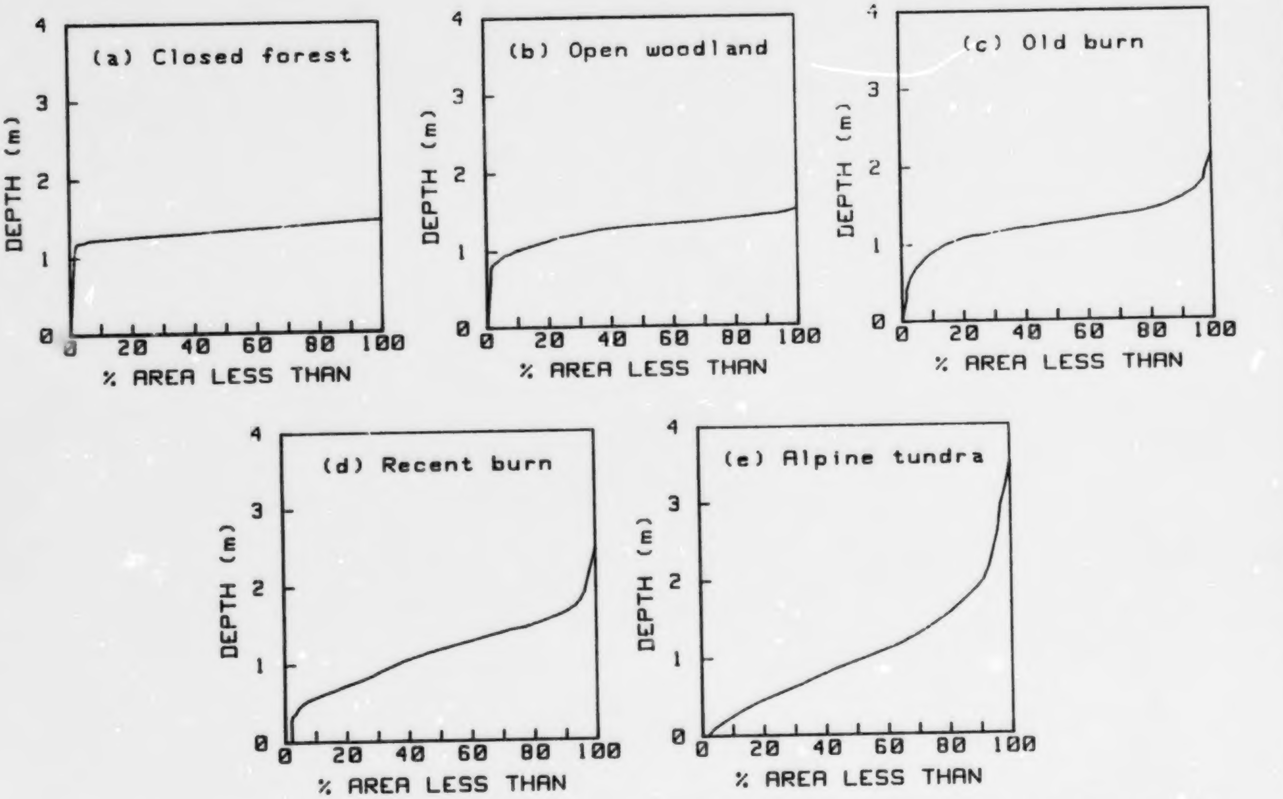

FIG. 3. Spatial differentiation of snow depths in different environments. The sequence illustrates the effects of surface roughness changing from high in closed forest (a) to low in alpine tundra (e).

peratures, and prevention of excessive winter heat loss from the soil. Meanwhile, the ecological horizon above the snow cover is affected adversely by the snow cover which can significantly lower the winter temperature in the near-surface layers of the atmosphere.

At Schefferville, snow/ground interface temperatures in open spruce woodland have been studied in considerable detail using grid surveys of approximately 10 rows by 10 columns with measuring points spaced 1 m apart. The average temperature at the interface was -2.8°C in December 1984 with a range from -12.7° to +1.0°C (below the moss cover). In February the average temperature was -1.5°C with a range in temperature from -9.9° to -0.1°C. In April the average temperature had risen to -0.9°C with a range from -3.0° to 0.0°C (Desrochers and Granberg 1986).

Different species develop different degrees of cold tolerance. A general review of winter hardiness in plants is given by Levitt (1956). Frost hardiness depends on the degree of development of the plant when the first frost occurs and it has been shown that the early frosts induce further developments of this frost hardiness (Larcher and Mair 1968, Sakai 1970). Different parts of the plants develop different degrees of frost tolerance. The aerial parts of northerly trees such as pine, spruce, and birch have developed an ability to survive at temperatures of -50°C or colder, while their root systems suffer damage at much higher temperatures. Many plants cannot withstand soil temperatures below the freezing point. Winter soil temperatures are usually more critical to seedlings than to mature trees because the whole root system of the seedling is near the soil surface where the coldest temperatures occur. Since snow is a main factor controlling soil temperatures, the snow cover thus extends northward the northern limit for most plant life.

The thermal effect of the snow cover is also felt during the summer season. It is particularly important to soil temperatures at the beginning of the growing season but its influence extends throughout the year. Apart from its direct effect on the individual plant, soil temperatures are important to the microorganisms in the soil which are responsible for most of the release of nutrients. Their metabolic rate depends greatly on temperature. The same is valid for the fungi symbiotically associated with different tree species. In some cases the northern limit of plants is determined by the northern limit of their mycorrhizal fungi (Kallio et al. 1971). There is also an influence of soil temperature on nutrient uptake (Cranham 1962, Carter and Cathwell 1967, Chapin 1972, Epstein 1972). The northernmost extension of several plant species in Alaska can be closely associated with warm spring areas (Hulten 1968). Where soil temperatures are maintained well above the normal mean by man-made structures such as pipelines, increases in biomass production by as much as 500% have been recorded (McCown 1972). This strong influence of soil temperature may in many cases determine whether or not viable seeds will be produced by a particular tree in a particular year or whether or not a seedling will reach the necessary stage of maturity to develop sufficient frost hardiness to survive the following winter.

At Schefferville where the mean annual air temperature is approximately -5°C, permafrost aggradation occurs in areas where fires have removed the forest cover. In such areas permafrost is aggrading under those parts of the terrain where the snow cover is removed by snow drifting. Permafrost makes the ground less permeable to water percolation. The active layer therefore tends to be colder and more waterlogged and consequently more likely to cause root disturbance by cryoturbation. This provides an environment that is unfavorable to forest regeneration.

Several species of lichen can photosynthesize at temperatures below freezing. The optimum photosynthetic temperatures for several species of alpine and antarctic lichens is around +5°C (Lange 1965). All of the lichens tested had positive net photosynthesis even at several degrees below freezing (as low as -10°C for *Parmelia coreyi* from Victoria Land). Thus, lichens can probably photosynthesize beneath thin snow cover through much of the winter season. In the alpine tundra areas near Schefferville there is a distinct correlation between lichen color and winter snow depths with dark-colored lichens inhabiting ridge crests where the snow is shallow, then dark green, lighter green, and white lichens such as *Cladina alpestris* in order of increasing snow depths. The coloring of the lichens must greatly affect their thermal environment by its influence on their absorption of solar radiation. Seedlings and intranivean parts of trees can also photosynthesize, inside the snow cover at least in spring. Snow is a multiple-scattering, low absorptance medium and as such solar radiation penetrates deep into the snow cover where it is absorbed by twigs and other vegetation parts in the snow. The low thermal conductivity of the snow causes a steep temperature gradient to develop near the twig as a result of the absorption of radiant energy. The associated steep vapor pressure gradient causes evaporation of the snow immediately surrounding the twig and a greenhouse cavity develops. Measurements I took at Schefferville indicate that temperatures well above the freezing point can occur in such cavities on sunny days, even when the air temperature above the snow surface is well below freezing. Temperatures of up to +8°C were measured in greenhouse cavities using a small glass bead thermistor. While there may have been some radiation error influencing the thermistor probe itself, the measurements show that from a thermal standpoint photosynthesis is possible. The conditions for photosynthesis may be further enhanced in these cavities by a raised concentration of carbon dioxide inside the snow cover (Kelley et al. 1968).

Unfortunately, however, pathogenic fungi such as *Phacidium infestans* probably also enjoy a near-ideal environment in the greenhouse cavity. According to growth experiments by Bjorkman (1948), *P. infestans* thrives best at temperatures between +5° and +15°C. The measurements at Schefferville indicate that the greenhouse cavity offers a thermal environment that is much more favorable to the growth of this fungus than the previously assumed maximum intranivean temperature of 0°C.

MOISTURE CONTROL

The snow cover acts as a temporary storage of the winter's precipitation and this water is released at the beginning of the growing season in a fashion that depends on the spatial variation in snowpack water equivalent and the spatial correlation between snow water equivalent and melt factors. Both may change significantly due to forest removal.

During melt the snow cover becomes waterlogged in some terrain situations for shorter or longer periods. This waterlogging is potentially lethal to tree seedlings. Particularly susceptible to waterlogging are the concave, lower parts of sloping terrain and valleys, particularly in sections where a reduction in the steepness of slope occurs. Because of the relatively low permeability of snow the water table in the snow cover can rise considerably. At Schefferville, intranivean water tables greater than 2.5 m have been observed in valleys on the alpine tundra. In woodland, on account of the shallower and more permeable snow cover, the intranivean water table does not usually extend more than a few tens of centimetres above the ground surface. The duration of the elevated intranivean water table is also shorter. Because of the great amount of meltwater released and perhaps also because of ground frost reducing the permeability of the ground, closed depressions, which are often dry after the snow disappears, may be flooded to considerable depths during spring melt.

As a result of snowmelt the beginning of the growth season is characterized by an ample supply of soil moisture. This is also the time when newly established seedlings depend most on a secure supply of moisture because of their immature root systems. The groundwater level in seasonally snow-covered areas shows marked temporal variations, peaking during snowmelt with a steady decline through the summer. In areas of strong local topographic variations, forest removal can probably influence the local availability of soil moisture considerably by reducing the groundwater infiltration in convex, more elevated parts of the terrain. In dry summers, this could create problems for young seedlings on sandy soils.

The seasonal variations in the groundwater table associated with the snow accumulation and melt also influence the water levels of lakes and bogs. Through this effect the snow cover has a major effect on vegetation zoning, controlling the large-scale vegetation patterns. Smaller scale zoning patterns influenced by moisture supply from long-lying snowbanks have received more attention in the literature (Klikoff 1965, Savile 1972, Billings 1974). The influence of moisture supply on vegetation zoning, however, is not necessarily a direct effect of moisture alone. It is probably a far more complex affair involving transfers of nutrients between different parts of the terrain by moving groundwater and effects of temperatures and moisture on soil-forming microorganisms.

TRANSPORT/TRAFFICABILITY EFFECTS

The snow cover provides a smooth surface for long-distance transport of both organic and inorganic matter. In open terrain this is most important both in the dispersal of plant life and in the development of nutrient-rich soils in microclimatically favorable locations. The importance of this transport has been well recognized (Lind 1927, 1934; Savile 1956, 1961, 1964, 1972). Wind and drifting snow act as very efficient propellants capable of transporting virtually any normally occurring type of seed, including berries, and it can transport other vegetable matter, such as twigs and pieces of lichens, and soil particles up to a size of several millimetres in diameter. The source of this organic matter is dead or live vegetation protruding above the snow surface. Without the snow cover such transport would be impossible because of the rough microstructure of the ground surface. Erosion and deposition of such matter occur much in the same way as drifting snow is eroded and deposited. Both seeds and soil-forming debris are thus preferentially deposited in sheltered locations where the summer microclimate is favorable. The main source of mineral soil particles is ridge crests that have a shallow snow cover throughout the winter. In spring this snow cover is melted and/or evaporated due to absorption of solar radiation which also desiccates the surface of the frozen soil causing it to be easily eroded by snow particles drifting across the ridge crest. New fine material is brought to the surface each year by cryoturbation processes. A lag deposit of fairly coarse gravel commonly covers such wind-eroded surfaces.

Wind transport is particularly important in the revegetation of extensive areas that have been completely stripped of vegetation by severe fire or by glaciation. Such areas do not attract other important seed carriers such as animals or birds. In the case of extensive burns, wind dispersal has a double advantage in that seeds can be distributed over the entire burn as early as the following winter. This allows the new seedlings to establish themselves shortly after the fire and thus benefit from the nutrients released by the fire before they are removed by leaching.

Unfortunately, mycelium and disease-infected needles and twigs can also be transported along the snow surface. Seedlings protruding through the snow surface efficiently trap such drifting debris. Distribution patterns of infections by *Phacidium infestans* suggest that infection via such drifting debris may be an important cause of spread of this disease.

The influence of the snow cover on the wintertime mobility of large mammals has been discussed by Formozov (1946) and Pruitt (1970) among others. The main effect important in this context is that snow restricts the mobility of large mammals such as moose, reindeer, and deer. This can result in overgrazing of the area within which they move during the winter. This area becomes more restrictive with increasing depth of snow. Overgrazing of tree seedlings protruding through the snowpack usually does not kill the plants but can cause severe damage to commercial forest plantations. As winter progresses and average snow depths increase, snow trafficability conditions in open terrain become more favorable than those in woodland. Browsing on tree seedlings by moose would then tend to occur mainly in areas of shallow snow on convex parts of the terrain. These parts would also be favored by reindeer or caribou who, in the process of digging for lichens, might also damage tree seedlings either mechanically or by causing excessive local cooling of the ground.

GROWING SEASON CONTROL

The snow cover is an important factor controlling the length of the growing season, both by limiting the light available to plants beneath the snow cover and by keeping air temperatures low for plants above the snowpack. There are large regional variations in the importance of the snowpack depending on the total amount of snow on the ground and the plant species involved.

While some species can benefit by developing under the snowpack, others cannot. This gives the able species an advantageous, early start allowing them to complete their vegetative cycle before they need to compete with other species. A typical example is species within the undergrowth in southern deciduous forest which flower well before the trees or tree seedlings have developed their leaves.

In regions with shallow snowpacks, the air temperatures in spring are not depressed by snow to the extent they are in regions with heavier snow covers. While in the former regions the snow may melt too early, causing danger of frost damage, the onset of the growing season is rapid in areas of heavy snow cover and the cold and dry spring period is almost nonexistent (Havas 1971). The plants adapt to the different situations and prepare for maximum utilization of the shorter growing season (Tranquillini 1957, Billings and Bliss 1959, Mooney and Billings 1961, Warren Wilson 1966) and the buds begin to swell when still under the snow. While in shallow snow regions it may take more than a month for the vegetation to get started after the snow is gone, in deep snow regions it may happen within a week after snowmelt occurs.

In most arctic and alpine tundras there is a rather specialized flora associated with long-lying snowbanks (Polunin 1948, Gjaerevoll 1956). The zonation of species is largely a result of adaptations to the depth and duration of annually recurring snowbanks (Billings and Bliss 1959). The plants must be able to complete at least a vegetative life cycle in a few weeks and even that may not be possible every year. An important consequence of long-lying snowbanks is that they hinder the establishment of seedlings (Tranquillini 1957, 1959).

MECHANICAL EFFECTS

The main ways by which snow affects vegetation mechanically are through abrasion by drifting snow and through loading and bulk motion of snow. During drift transport the velocity with which the snow particles move depends on the wind speed near the surface and can reach 15–20 m/s. At this velocity, snow is an efficient abrasive agent, particularly at low temperatures as the hardness of the snow crystals increases rapidly with decreasing temperatures. The snow abrasion is strongest close to the snow surface where the snow transport rate is greatest and the size of the transported grains largest. It declines rapidly with height. The height to which the snow abrasion zone extends above the surface varies from a few tens of centimetres to a few metres depending on terrain situation and wind conditions. Damage by snow abrasion to forest plantations in northern Sweden have been documented by Holm and Kullman (1983).

One feature created by snow abrasion is the "wind gap" in spruce trees. It is characterized by a lack of branches along a portion of the stem. The lower limit of the wind gap coincides with the depth of snow after long-distance drifting has become possible. The upper limit of the wind gap is less distinct and varies in height depending on terrain situation. The snow abrasion zone is very difficult for seedlings to transcend. Tree-ring analysis at Schefferville shows that the difference in age at the base and at breast height of trees in the alpine tundra margin may be more than 200 yr (Warren 1981). For a seedling to become a tree in this environment a sufficiently long sequence of years without severe cold-weather snow abrasion events is needed to allow the top of the seedling to reach above the snow abrasion zone.

The "hedge-trimming" of shrubs near ridge crests on alpine tundra is also caused by snow abrasion. A survey at the Timmins 4 Permafrost Experimental Site near Schefferville shows that the mean maximum height of stems of dwarf-birch is closely related to the depth of snow in winter. The height of plants is less variable near ridge crests, where the snow depth is near-constant through the winter and from one winter to the next (Granberg 1972). Away from the ridge crests the variation in plant height increases as does the variation in snow depth. On the parts of the Timmins 4 site that are kept snow-free through the winter not even lichens survive, except for some rock lichens in sheltered crevices between rocks. Grab samples of vegetation debris cresting snow dunes after heavy winter storms at Schefferville show that live dwarf-birch twigs of up to 3 mm in diameter can be broken by drifting snow at low temperatures.

Loading affects vegetation extending above the snow to different extents depending on the vegetation type. Some pine forests, for example, are more prone to damage by snow-loading than are spruce and fir forests because on some species of pine, for example, *Pinus silvestris*, the branches grow upwards, while on spruce and fir they grow more or less horizontally. When the snow load increases, the branches on spruce and fir bend downwards, reducing the intercepting area and also allowing the snow to slide off the branches. When pine branches are bent down by snow, the intercepting area increases and the branches have to bend much farther before the snow can slide off.

Deciduous forests are usually less affected by snow-loading than coniferous forests because of the generally smaller area available for snow accumulation after the leaves are gone. If heavy snowfalls of sticky snow occur before the leaves are gone, damage is much more likely. Deciduous trees, however, often have a branching structure that makes them more prone to damage by icing storms than are most coniferous trees. As well, the trunks and branches are often inclined rather than vertical as is the case with most coniferous trees. The susceptibility of trees to damage by loading depends greatly on whether the individual tree grows vertically or not. If in a dense forest one tree is bent over, it is in a position to intercept more snow so that it is more likely than its neighbors to be snow-thrown. Should this happen, a domino effect may occur. The break in the canopy causes adjacent trees to grow asymmetrically. These trees in turn can thus become more predisposed to bending and breaking by snow-loading.

Seedlings are particularly susceptible to damage by snow-loading and are quite easily bent over. When further snowfall occurs they may be buried in the snowpack. As the snowpack settles, they are bent further and may break.

Snow on slopes slowly creeps downhill during the winter and in doing so bends seedlings and young trees in a downhill direction. More spectacular damage is produced by avalanches. They can break trees of any size along their path. Usually avalanches recur annually or within a few years' interval along the same path creating characteristic differences in vegetation. Avalanche paths are favored by annuals and woody plants with tough, springy stems (Potter 1972).

The settling of the snow cover often occurs in a step-wise fashion, with the snow settling in increments of several centimetres. Such settling produces high strain rate on branches in the snow and may cause cracks where a branch joins the stem of the seedling. These cracks may allow infection by pathogens.

CHEMICAL EFFECTS

The very large specific surface area of the atmospheric snow makes it an efficient scavenger of gases, droplets, and particulates during its fall toward the ground. Once deposited, a rapid reduction in surface area of the snow begins. This could lead to "degassing" of surface-absorbed gases. It could also lead to a concentration of other surface-absorbed substances.

In the case of snow lodged in tree crowns, absorption of solar radiation by the trees causes evaporation of this snow. As the snow evaporates, the snow contaminants are concentrated onto the needles and branches. The contaminants are not diluted or removed until rain or melting of intercepted snow occurs.

Because of ventilation of the surficial layers of the snow cover, a filtering effect was proposed by Gjessing (1975). Such filtering would probably also occur in snow lodged in tree crowns and might further increase the contamination of such snow. When intercepted snow melts or when residual contaminants are rinsed off the tree crown by rain, the contaminants are deposited near the tree, quite often in quite concentrated form. The contaminated water seeps into the frozen ground where further concentration may occur by freeze-out of water. The liquid residue is added to the liquid soil water component which is used by the trees in winter.

As a result of the vapor pressure/temperature gradient through the snow cover, parts of the ice skeleton are evaporating while other parts are growing by sublimation. This offers a possible mechanism by which snowpack contaminants may be concentrated at the surface of the ice skeleton (Colbeck 1981). The acid flush that may occur in early melt and its effects on streams and lakes have been discussed in the literature (Johannesen and Hendriksen 1978). The potential effects of such events on seedlings and trees are unknown. However, it may be anticipated theoretically that much of the contaminants that are released early in the melt will enter and be retained by the soil as a result of wintertime cracking and desiccation of the near-surface layers of the ground.

Conclusions

This paper shows that the snow cover is an extremely important factor influencing forest plants throughout their life cycle. The significance of the intranivean and subnivean microclimates to plant and animal life cannot be overstated. Without the seasonal snow cover, many plant species and a great many mammals who currently thrive far into northern latitudes would be absent from the Canadian scene altogether.

There are multiple links between snow cover and climate. First, the physical characteristics of the snow cover are largely determined by the local climate and microclimate.

Secondly, the snow cover controls both the supranivean, the intranivean, and the subnivean microclimates. Many of the mechanisms linking snow cover and forest plants are not well known and should be explored in detail, not only to avoid potential adverse effects of large-scale forestry operations in northern environments but also to reach maximum efficiency in reforestation projects and in overall forest management.

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Timing and Impact of Aerial Herbicide Spraying on Black Spruce in the Great Clay Belt of Ontario

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Abstract

The control of competing vegetation with aerial herbicide applications, to ensure the survival and growth of planted stock, is an indispensable part of silviculture in Northern Ontario, especially in the Clay Belt section where poor drainage and rich clay soils lead to severe competition problems. Timing of the spray to maximize impact on the target species, and to minimize adverse effects on the crop trees, is essential. A model using cumulated degree-days to predict the phenological development of black spruce (*Picea mariana* (Mill.) B.S.P.) and speckled alder (*Alnus rugosa* (Du Roi) Spreng.) was developed and calibrated for Kapuskasing District, using data collected by Spruce Falls Power and Paper Company. The model and its utility in forest management planning are considered. Ongoing research to refine the model and to investigate the impacts of aerial herbicide application on the performance of black spruce plantations, over a range of dosages and application dates, is discussed.

Résumé

La lutte contre la végétation concurrentielle par des pulvérisations aériennes d'herbicides pour assurer la survie et la croissance du matériel planté constitue une partie fondamentale de la sylviculture dans le nord de l'Ontario, particulièrement à l'intérieur de la ceinture d'argile où le mauvais drainage et l'existence de riches sols argileux occasionnent de graves problèmes de compétition. Il est essentiel d'effectuer les pulvérisations au moment approprié, afin de maximiser l'impact sur les espèces cibles et de minimiser les effets négatifs sur les arbres de plantation. Un modèle qui utilise des degrés-jours pour prédire le développement phénologique de l'épinette noire, *Picea mariana* (Mill.) B.S.P., et d'aulne blanc, *Alnus rugosa* (Du Roi) Spreng., a été mis au point et étalonné pour le district de Kapuskasing à l'aide de données recueillies par la Spruce Falls Power and Paper Company. On examine le modèle ainsi que son utilité pour la planification de la gestion forestière. On aborde la recherche en cours visant à améliorer le modèle et à étudier l'impact d'une gamme étendue de doses et de dates d'application aérienne d'herbicides pulvérisés sur le rendement des plantations d'épinettes noires.

Introduction

Aerial application of herbicides to control competing vegetation on black spruce plantations in the Great Clay Belt of Ontario, Northern Region, is an indispensable part of silviculture programs. In the Clay Belt, severe competition is usually encountered on the rich, moist clay soils following harvesting and mechanical site preparation. Follow-up tending for control of competing vegetation is almost always required, if regeneration efforts are to succeed. As a result, the aerial spray program is an integral part of the total regeneration effort.

This fact has important implications for the Prime Land Management Program (Raitanen and Calvert 1984) currently in place in the Ministry of Natural Resources' Northern Region. This program is intended to direct intensive forest management practices to prime lands, which are the most productive sites closest to the mills, access corridors, and population centers. Most of the sites with a highly productive tree growth also support very large populations of competing vegetation, and will require tending in some form to maximize growth and yield, probably at a considerably increased cost. Timing of the spray, in terms of optimizing impact on the target vegetation, and minimizing the amount of herbicide damage that occurs as a result of the aerial spray applications, is of critical importance.

This paper focuses on two studies. The first was a preliminary study conducted for Spruce Falls Power and Paper Company, Ltd., located at Kapuskasing in the heart of the Clay Belt. From 1982 through 1984, Spruce Falls tested 2,4-D herbicide spraying in an early season (May) application, for control of speckled alder (*Alnus rugosa* (Du Roi) Spreng.) on low-ground sites. This was done for two purposes: (1) to extend the limited season available for herbicide spraying, and (2) to attempt to use less herbicide earlier in the season when the target vegetation was just emerging.

Based on the results of the preliminary study, a research project was initiated, co-funded under the Canada–Ontario Forest Resource Development Agreement (COFRDA) by the Ontario Ministry of Natural Resources and the Canadian Forestry Service, and conducted by Ecological Services for Planning Ltd., at Timmins, Ontario, in cooperation with Spruce Falls Power and Paper Company.

The objectives of the study are:

1) To better define the spray windows for the chemicals 2,4-D and Vision® (glyphosate), by quantifying the phenological stages of development of both the target and the crop species, and correlating development with various climatic variables, to see whether the stages can be predicted.

2) Investigation of the application rates of the two chemicals for determination of their impacts on both target and crop at various stages of development, for planning timing of the spray and the appropriate dosage.

3) Examination of the effects of site on phenological development.

Herbicide Tending in the Northern Region

An overview of the current state-of-the-art large-scale aerial spray programs in the Northern Region, using Kapuskasing District as an example, is presented in Figure 1. There are two herbicides that are currently available for aerial application in forestry in Ontario, Vision® and 2,4-D. Vision® is applied primarily during August, on upland sites, and is aimed at target species which include hardwood regeneration (primarily trembling aspen and balsam poplar), grasses, sedges, and raspberries. These competitors are not effectively controlled by 2,4-D.

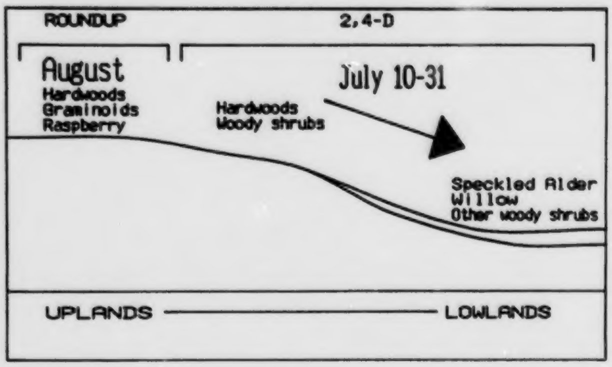

FIG. 1. Overview of aerial herbicide spraying, Kapuskasing District, Northern Ontario.

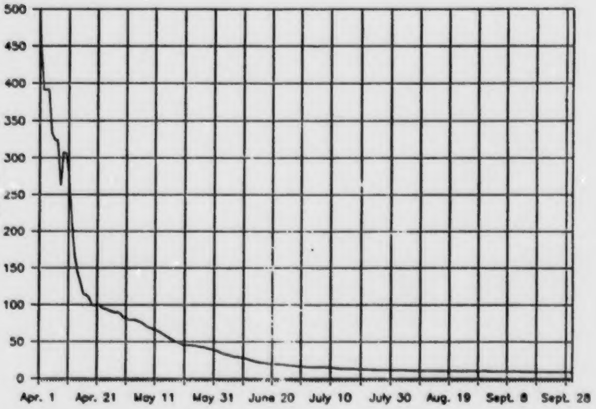

FIG. 2. Coefficient of variation for cumulated degree-days exceeding 5°C for 1951–80.

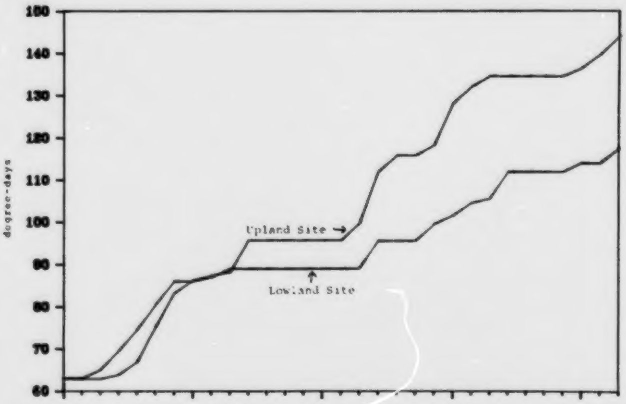

FIG. 3. Cumulated degree-days exceeding 5°C for May 1984 at the Agriculture Canada experimental farm at Kapuskasing, Ontario (upland site), and at Spruce Falls' Camp 80 (lowland site).

The normal release spraying window for 2,4-D takes place between approximately July 10 and 31. The program proceeds sequentially from the upland to the lowland sites, to take advantage of the differences in phenological development between the uplands and the lowlands. Development on the lowlands lags behind that on uplands by approximately 1 wk. On the uplands, the main targets are hardwood regeneration and other woody shrubs (including *Acer spicatum*, *Prunus pensylvanica,* and *Corylus cornuta*), which are moderately susceptible to 2,4-D applications. On the lowlands, the prime target is *Alnus rugosa*.

Operational Constraints

Within the industry, there are several key operational constraints imposed on aerial spraying programs. Some of the main problems include the high cost of the chemicals, which is particularly important considering that the newer chemicals coming onto the market, such as Vision,® are approximately 10 times more expensive than 2,4-D. Spraying 2,4-D currently costs approximately $10–12/ha, whereas Vision® tending costs between $100 and $120/ha.

The second factor that creates logistic constraints is simply the magnitude of the spray programs. Equipment downtime can become extremely expensive. Due to the size of the operation, much of the work is done by contractors. Therefore, less flexibility is available for scheduling than with internal operations. This means that sometimes compromises must be made on certain sites, in terms of reduced impacts on target vegetation through missing the ideal spray window.

Regarding the planning aspects of a spray program, scheduling of machines and manpower is a problem because the predictability of the spray window is currently unknown. Implementing new methods and technology involves large-scale training programs for ground personnel. Controlling the progress of the spraying to the proper sites at the proper time requires advance planning. This is complicated because different chemicals have different spray windows. Effective application rates for different chemicals must be determined to order chemicals in advance.

The problem is how to maximize the effect of herbicide application at minimum cost. Three aspects are critical: timing of the spray (spray windows), dosages necessary to optimize the effect, and impacts of the application, in terms of both physiological effect on target and crop plus costs.

Application of new technology in the forest industry proceeds in three phases. These include a development phase, during which new ideas from the research community or elsewhere are adapted to their own particular needs; second, new technology, once it is developed to the point where they can apply it, has to be incorporated into the planning structure; and third, new technology, once developed and incorporated into the planning structure, must be transferred to the operations level. This usually involves extensive training programs for field staff.

Climatic Variability at Kapuskasing

One of the problems associated with predicting the timing of spray applications is the variability in climate, especially in the spring when the "early spray window" occurs. This is illustrated in Figure 2, which shows the coefficient of variation for cumulated degree-days exceeding 5°C, for the 30 yr from 1951 to 1980. The graph shows that in the early part of the season, the number of degree-days accumulated at any point in time is variable and does not start to stabilize until July.

Another problem that must be addressed is the differences in microclimate between topographic site types. This is illustrated in Figure 3, which shows cumulated degree-days exceeding 5°C, for May 1984, for an "upland" vs. a "lowland" site. The "upland" data is derived from weather records at the Agriculture Canada experimental farm at Kapuskasing, which is located on an elevated uplands site, vs. fire weather data taken from Spruce Falls' Camp 80, which is located in a "lowland" (peatland) site. There is a considerable lag in the peatland regarding the accumulation of degree-days, corresponding approximately to a 5- to 9-d lag in the phenology of both black spruce and *Alnus rugosa*.

Preliminary Results from the Spruce Falls Feasibility Study

A review of the agricultural literature revealed a possible approach to the problem. The initiation of plant growth is closely related to air temperature. For example, in fruit trees, bud break and blossom development are a function of air temperature (Anstey 1966). A common agricultural baseline for accumulating degree-days is 5°C (41°F). Arbitrarily choosing this temperature as a baseline, degree-days exceeding this critical value were accumulated on a daily basis, and correlated to the development of both speckled alder and black spruce, to develop a preliminary model for predicting the development of these species. Climatic data and data pertaining to the phenological stages of alder and black spruce were obtained from the Agriculture Canada station at Kapuskasing and Spruce Falls, respectively. Phenological data from Spruce Falls was available only for the 3 yr from 1982 to 1984.

Table 1 shows the classifications used for black spruce and *Alnus rugosa* to assess their development.

TABLE 1. Descriptions of the classifications used to record the developmental stages of black spruce, for the early spray development work, corresponding to the stages indicated in Figure 4.

Species	Stage of development	Description
Black spruce	1	Buds fully dormant
	2	Buds have become shiny or glossy
	3	Buds swelling, with green and brown flecks
	4	Buds burst (>50% of buds)
	5	Short shoot elongation
	6	Full extension of the main leader
	7	Buds set but not yet hardened
	8	Leader fully hardened off
Alnus rugosa	3	Buds swelling
	4	Buds breaking out of cases
	5	At least 50% buds broken, some miniature leaves
	6	100% buds broken, partial leaf expansion (miniature leaves)
	8	Fully flushed with leaves fully expanded

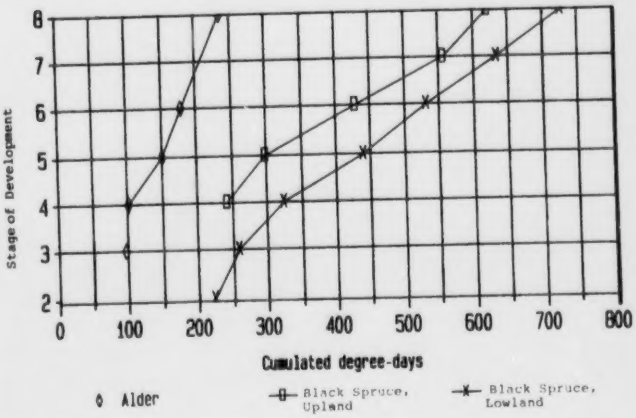

FIG. 4. Development stages of black spruce (*Picea mariana* (Mill.) B.S.P.) and speckled alder (*Alnus rugosa* (Du Roi) Spreng.).

TABLE 2. Hypothetical activity table for aerial spray program, based on mean cumulated degree-days until important life cycle events, for alder and black spruce.

Life cycle events	Action	Mean cumulated degree-days	Actual range of times for events: 1982–85
Alder miniature leaf stage	START EARLY SPRAY	175	May 26 June 3 June 5 June 12
Black spruce buds burst on low ground	STOP EARLY SPRAY	320	June 12 June 18 June 22 June 23
Black spruce buds setting on high ground	START RELEASE SPRAY -HIGH GROUND	555	July 10 July 10 July 13 July 13
Black spruce buds setting on low ground	START RELEASE SPRAY -LOW GROUND	630	July 16 July 17 July 18 July 20

The number of degree-days accumulated at each developmental stage was averaged over the 3 yr, and used to develop the model illustrated in Figure 4. Cumulated degree-days on the X-axis are plotted against phenological stages for *Alnus rugosa* and black spruce, on both "upland" and "lowland" sites, respectively. Development of black spruce on the lowland sites lags behind that on the uplands by about 1 wk. The development stages of black spruce and alder shown in Figure 4 correspond to those given in Table 1. From this simple model, a hypothetical "activity table" for the aerial spray program can be developed (Table 2).

The "early spray window" for black spruce occurs between the alder miniature leaf stage, at which acceptable alder kill is achieved (stage 6), and the point at which the spruce buds burst (stage 4) and become susceptible to spray damage. The normal release spraying window occurs after budset (stage 7), at which point, presumably, the potential spray damage is minimized. This assumption is currently untested.

The model can be used by adding the number of degree-days each year, starting at the beginning of April. Predictions of the expected date(s) of occurrence of the various phenological event(s) can be made at any time using the following formula (Anstey 1966):

$$D = (T - A) / M$$

where D = the predicted number of days from the current date until the event;
T = average number of degree-days to the event (from a table based on 35 yr of climatic data, from 1951 to 1986);
A = number of degree-days accumulated by the date of prediction;
M = average number of degree-days accumulated per day from the prediction date to the date of the event (from a summary table of historical data).

The accuracy of the equation's prediction increases as the season progresses, and the temperature variance becomes less. Although it seems possible to predict the progress of phenological development in both alder and black spruce, there is at present insufficient data to know exactly what the results will be, should aerial herbicide spraying be conducted at various stages of development of these species.

Summary

A preliminary model for predicting the development of black spruce and *Alnus rugosa* was derived from 3 yr of data collected by Spruce Falls Power and Paper Company, at Kapuskasing. This model must be tested and refined. If it works, it can be used to predict the timing of aerial spray windows for advance planning of spray operations on an annual basis.

A research study has been initiated under the auspices of the COFRDA agreement to investigate several aspects of aerial herbicide tending of black spruce in the Clay Belt of Ontario.

Several key questions are being assessed. At different herbicide application rates, what effects on both the target and the crop species can be anticipated, and what impact is that likely to have in terms of growth and development and survival of the crop species? How can the preliminary model be refined to improve the accuracy of prediction, and what accuracy can be expected?

These questions must be addressed before cost/benefit analyses of herbicide tending can be performed. Cost/benefit studies are necessary to determine the need for tending in Northern Ontario, and the risks associated with not tending. To ensure effective technology transfer, close contact with both planning and operations staff of the forest industry and government agencies must be maintained for the duration of the study.

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Thermal Stress in the New Forest

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Abstract

Climate directly infuences tree growth and development. Growth layer analysis (TRIM technology, Ministry of Natural Resources) of replicated whole tree plots describes the growth and development processes as a function of species-spacing, soils, and thermal stress. Thermal stress is defined by the previous October and current April mean temperatures for jack pine (*Pinus banksiana* Lamb.) and by the previous September and May mean temperatures for spruce in Ontario. Management implications are highlighted both for temporal forecasting of yearly cambial activity and for spatial mapping for thermal stress regions.

Résumé

Le climat a un effet direct sur la croissance et le développement des arbres. L'analyse de la couche d'accroissement (système technlogique TRIM du ministère des Richesses naturelles) étudiée par répétition, dans des placetes d'arbres entiers, décrit les processus de croissance et de développement en fonction de l'espacement des espèces, des sols et du stress thermique. Le stress thermique est défini par les températures moyennes du mois d'octobre précédent et du mois d'avril courant pour le pin gris (*Pinus banksiana* Lamb.) et par les températures moyennes du mois de septembre précédent et du mois de mai pour l'épinette en Ontario. On insiste sur l'importance en gestion des prévisions temporelles de l'activité annuelle du cambium et de la cartographie spatiale des zones de stress thermique.

Introduction

Trees are opportunists. In particular, trees are designed for maximum efficiency when young. It is unfortunate that this design does not continue with the same efficiency as the tree matures. Put another way, an engineer's solution for the analysis of growth responses over time is unrealistic. Otherwise productivity would not slow down with age and linearity of the growth response would prevail.

In reality, the selection of survivors and the identification of candidates for mortality happen at an early age as the young trees are struggling for light, temperature, moisture, and space. Additional stress can and will accelerate tree stagnation and if independently severe or coincident will lead to mortality. Unquestionably, the life of a tree within a stand is not an easy one.

If we reexamine the primary climatic variables that drive forest production then our attention is focused on radiation, temperature, and moisture. Photosynthetic capacity of the forest stand responds to both thermal and moisture interactions. Several authors have demonstrated this basic relationship between various photosynthetic indices and wood production. However, the degree of response is principally governed by the current stand structure (species-spacing), stand history, and other site and environmental limiting factors. Very quickly this scenario can evolve into an appreciation and detailed study of the complexity of the total forest ecosystem.

Although preferred, this is not the practical intent of this paper. Instead, the focus is thermal stress effects on new forest growth and development but within the context of stand structure, soils, and climate. By focusing initially on these three macrofactors and by isolating their individual and interactive influences, other coincident stress events can be identified that impact on growth responses in the new forest. This is definitely a hierarchical process by which we first attempt to understand what we can, then address departures or residual patterns separately.

Biological data bases must exhibit consistency in data recording, sensitivity to the biological processes, and precision for analytical forecasting. The failure to meet these requirements will mask the temporal variances owing to species-spacing, soils, climate, and their integrated influence on wood production. The interaction of each of these factors is equally and, in many cases, more important than any one individual element. The understanding of this interaction also depends largely on the related precision and scale of the measured parameters.

Scarce data sets currently exist within the timber land base which meet the above biological and analytical requirements. To unravel these biological responses over time required the development of a computerized Tree Ring Increment Measuring (TRIM) System (Fayle and MacIver 1986).

Management implies direction. To direct one or more of these macrocausative parameters assumes an understanding of their interrelated processes coupled with the intended management activity timed according to the current stage of development of the forest stand. It is the dynamics of forest growth functioning in response, for example, to the synoptic environment which dictates the need for the physiological interpretation of growth and development based on a dynamic rather than a static understanding — both for the individual tree and trees aggregated on a unit area basis.

Within this context, climate plays a major role with direct impact on forest growth and development. Certainly not a new or profound statement, yet little understanding of the climatic management options available to the forester are practiced in forestry today. In many cases the antiquated philosophy that "we can't change the climate" prevails. If sustained investment/returns or accelerated responses are expected when compared with the natural stands the scheduling of forest management activities must be "in sync" with the dynamics of the synoptic environment. For example, the monitoring of atmospheric stress conditions should be a basic determinant for silviculture activities.

At the strategic level, the options available to the forester are restricted to changing either the species and/or the site. In the latter case, this most certainly includes treatments (i.e., fertilization) and site selection (i.e., macroclimate/microclimate), whereas in the former case genetic manipulation is but one example. At the same time, the forester must be aware that sites defined exclusively by soil are changing in response to climatic fluctuations.

At the tactical level, the forester continues to be faced with a host of climatic parameters and the recurrent question is often asked, but which parameters are important for forest growth and development? For example, historical and standardized climatic data bases have been assembled for several points within the atmospheric landscape. This relational data base is a key reference at the unit area scale for analytical forecasting of the forest estate. Within this biological context, the climatic parameters important to the growth processes are the focus of this paper. But as stated earlier, the identification of these interactions will be addressed and linked with the current species-spacing structures, physiography, and physical soil environments to document the temporal patterns and mapping of the spatial relationships. Detection of departures from these interrelated patterns will verify anticipated improvements or indicate the need for specific remedial actions at a particular time in the stand's development. In all cases, the timing of the management activity must be flexible to reduce the cumulative stress effects within this dynamically changing forest environment.

Sampling Designs for Biological Response

Critical to the TRIM growth layer analysis procedures are the destructive sampling of all trees within replicated plots per stand, the sectioning of trees at sufficiently close intervals to document the detailed radial and longitudinal patterns of growth, the replicated cardinal radii measurements per tree-disk section, and the unit area mapping of all species. This sampling design recognizes the clustered spatial distribution of the forest estate and the retention of the forest community as the basic unit for reconstruction analysis over time.

Specifically, this biological data base is derived from four randomly replicated 20x20 m plots with an inner destructive sampled area of 10x10 m. All species within this inner area were measured with the TRIM System. Additional within-tree and within-disk sampling designs are outlined in a later presentation (MacIver et al. 1988).

Numerous forest stands for jack pine and black spruce have been assembled into a numerically sound data base for the boreal region of Ontario. Randomly replicated unit area sampling is a basic requirement for reconstruction methodologies, especially when aggregating to the stand performance level. For example, on medium to fine sand jack pine stands from Gogama, Ontario, acceptable numeric stability was achieved when the 95% confidence length falls below unity.

Increasing the number of replications as opposed to increasing the plot size is strongly recommended where forest stands exhibit clustered distributions. As a value-added benefit, this multiuser unit area sampling design allows for post subsampling/aggregation linkages with traditional mensurational forestry data bases for the purpose of calibration and putting "in sync" existing empirical yield functions.

Species-Spacing

The traditional mensurational parameters of stocking/density are poor measures of the spatial distribution of trees by unit area in the new forest. The pattern of this distribution of crop trees in competition with themselves or other species has a significant impact on forest growth and development.

Treplot unit area graphs were developed to demonstrate this high degree of clustering which is a characteristic fingerprint of highly productive jack pine sites. Figure 1 presents an example of these Treplot graphs and depicts the tree crowns (average width) for all species by their X, Y coordinates (ground survey) plus the stratified jack pine crop species locations.

Fundamental to the calculations of a species-spacing index is it's ability to stratify distributions into uniform, random, or clustered stratum (Fig. 2) but, more importantly, this index must also be sensitive to contributions of each individual component. For example, the species-spacing algorithm can be conceptualized as a species space in which the three basic forms (uniform, random, clustered) are increasing axes in a multidimensional space. As the percentage contributions of each form approaches the centroid, then productivity understandably declines.

For example, the relationship between species-spacing and jack pine productivity at 18 yr can be summarized as follows:

1. Competition of jack pine species with other species is detrimental to the jack pine crop tree when all of the following conditions occur simultaneously: (a) the "other species" competition share the same space as the jack pine; (b) the "other species" competition are **above** the mean base of live crown of the jack pine; (c) greater than 50% of the "other species" crown canopies interact with neighboring jack pine canopies.
2. Competition of jack pine species with its own species is detrimental to the jack pine crop tree productivity by 18 yr when either (a) jack pine stems are completely surrounded by other jack pine; (b) jack pine stems are surrounded on at least three sides **and** other species compete with it for this free area.

Before this point in time, the "enclosed" jack pine clearly demonstrated biological stagnation (diagnosed by the TRIM System) as noted in the separation of the "effective crown base" from the base of live crown.

"The configuration of the growth layer profile (GLP) for area together with that for width can provide information on crown development. Our evidence in Jack Pine (and Red Pine) suggests that the location of maximum cross sectional area of the GLP, or where the curve changes shape, usually occurs higher than the live crown base is perhaps an indication of the effective crown base." (Fayle and MacIver 1986)

In comparison, visual or standard mensurational surveys taken at recurrent intervals detect changes in stand structure at a point in time normally too late for effective management.

This species-spacing algorithm, calculated from the treplot unit area graphs, demonstrates the dominant influence of stand structure on forest growth and development. Unit area mapping is highly recommended by the author as an essential ingredient in forest productivity studies.

Soils

Similar to the above discussion, limiting physical soil conditions can exhibit a dominant stress on forest growth and development patterns. In all unit area plots, physical and, where possible, chemical laboratory analysis was a recurrent ingredient of the TRIM data bases.

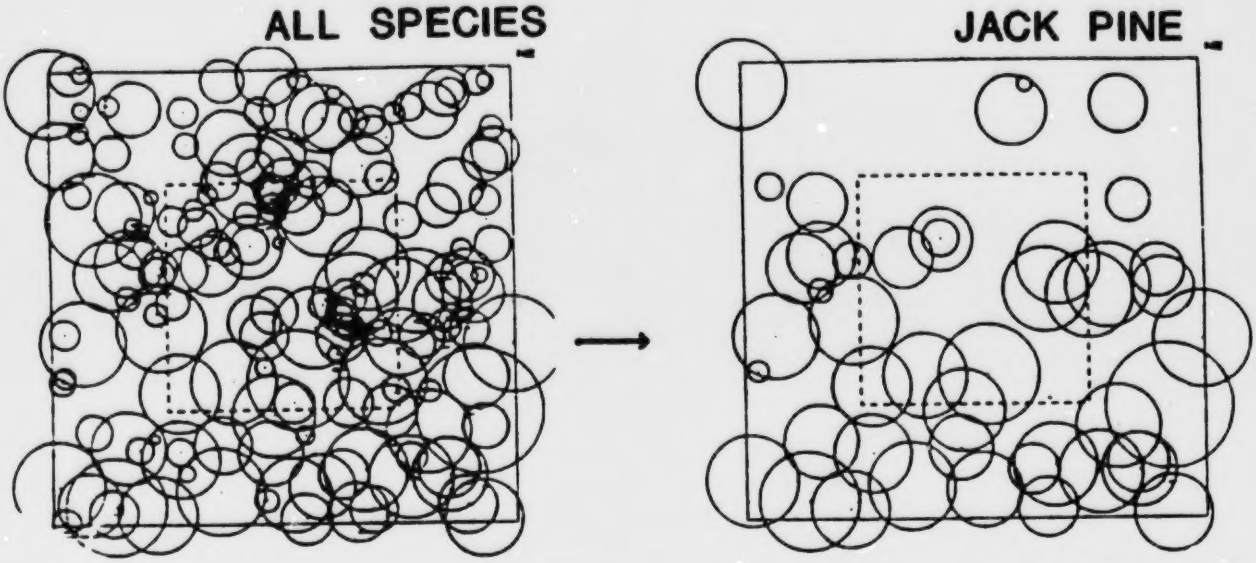

FIG. 1. Unit area mapping of all species within 20x20 m sample plots plus stratified mapping on only the jack pine spatial distributions. Inner dashed lines represent the 10x10 m destructively sampled area for all species.

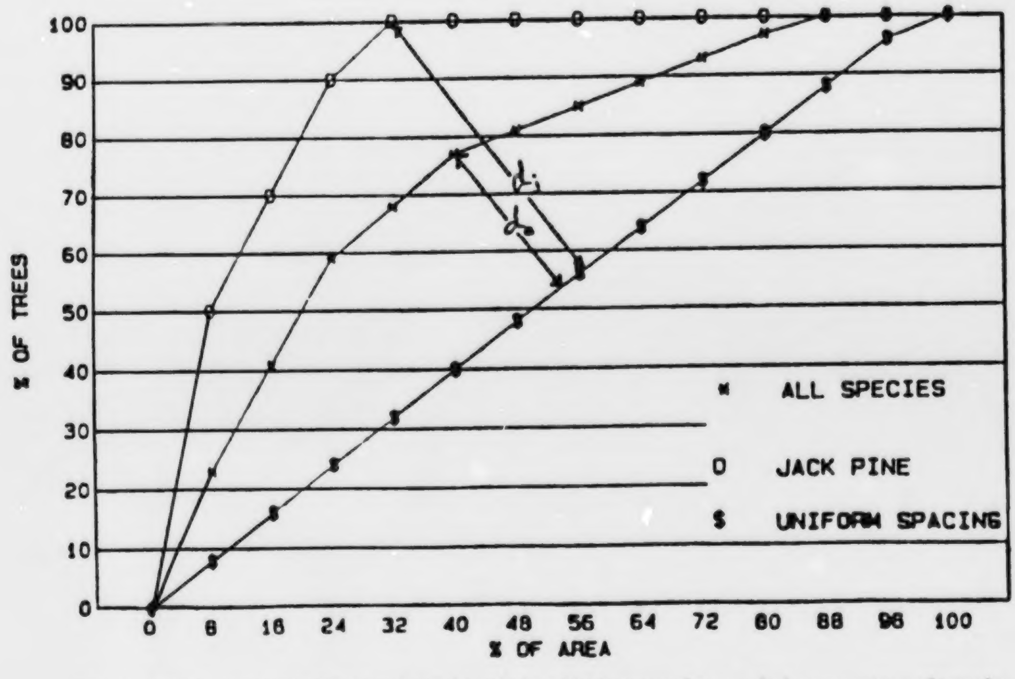

FIG. 2. Species-spacing index based on the relationship between the cumulative percentage of trees by cumulative percentage of area occupied.

However, a word of caution is expressed where soils productivity cause/effect relationships are anticipated without prestratification of the forest growth patterns by species-spacing (stand structure) and climate. For example, in four replicated jack pine plots located within the same stand (same microclimate/macroclimate), the spatial distribution of species explained the significant cumulative differences in volume productivity, whereas climate explained the significant yearly fluctuations.

Complete physical and chemical descriptions per plot/stand are essential for the partitioning of volume growth responses. Separation in the volume curves owing to soil (and climate) influences occurs much earlier in the growth chronologies compared to that of competitional influences.

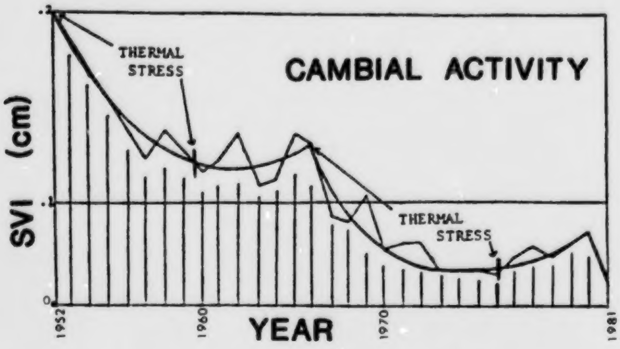

FIG. 3. Thermal stress periods are defined by the previous October and current April mean temperatures compared to Specific Volume Increment (SVI) response (1952–1981) for jack pine.

Soil descriptions are strongly suggested as standard inventory procedures before silviculture site preparation.

Climate

Climate directly affects forest growth and development. As noted earlier, the photosynthetic capacity of a forest responds to both the thermal and moisture conditions persistent at that geographical location. Long-term climatic data is an invaluable relational base providing both the temporal and spatial linkages with forest development. This current model draws on previous climatic analysis for Ontario in which "broadened climatic data bases have been assembled, analyzed and documented for 105, 30-year climatic stations in Ontario" (MacIver and Masterton 1985).

Thermal stress is defined by the previous October and current April mean temperature departures for jack pine about their respective biological thresholds. Thermal stress relationships are different for other species. For example, black spruce are defined by their previous September and current May mean temperature departures (Fayle and MacIver 1986).

This relationship is illustrated in Figure 3 in which cambial activity, as defined by Specific Volume Increment (SVI), is compared to their respective thermal stress periods for jack pine. In this case, a shallow soil overlaying till was selected to illustrate the limited recovery capability during nonstress periods. In stands with little intraspecific competition on deep soils, the decline curve is much shallower within this inverted scallop with recovery equal to or exceeding the initial point at the commencement of the stress period. The degree of response is principally a function of the species-spacing status of the present stand structure at the time of the thermal stress event. Coincident with these thermal stress periods are bursts of incremental mortality and insect defoliation peaks. Substantial forest production improvement can be expected by reducing the competitive structure of the forest stand before the onset of thermal stress periods. The resultant form of this inverted scallop will be shallower with superior recovery during the subsequent nonstress period.

Biological fluctuations per year within these thermal stress periods are to be expected in response to the climatic conditions with lag periods principally a function of the physiological status of the trees within their current stand structure. Slowdowns tend to be immediate, whereas recovery is typified by at least a 2-yr lag response.

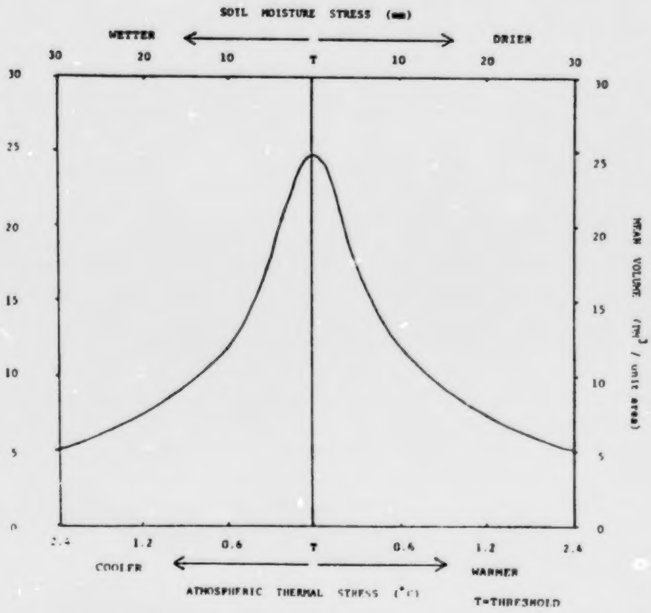

FIG. 4. Thermal and moisture stress monogram compared to mean volume for jack pine on medium to fine soils.

Only "healthy" highly productive stands were selected to document the environmental stress periods for mature jack pine stands from 1900 to the present. The temporal cycling suggests three thermal stress periods interrupted by short recovery periods with a longer period of recovery following the third stress episode. Since the 1900s the thermal stress periods have been elongating at the expense of the following recovery periods with an overall cycling of approximately 36–32 yr (note: there has been a slight shortening of each cycle). For example, the 4-yr thermal stress episode at the turn of the century has now become a 7-yr period.

The incremental change in climatic stress periodicity is more intensive now compared to the replicated pattern experienced in the late 1930s, 1940s, and 1950s when species dieback and slowdowns in stand volume increment were apparent during these back-to-back stress sequences. This acceleration in climatic stress episodes reinforces the hypothesis that the changing nature of the cycles and periods are perhaps a result of increases in global carbon dioxide, changing ozone and air pollution levels.

Regarding the new forest, more frequent delays in forest growth plus increasing individual tree stagnation can be expected at this early age but no reduction in the overall vigor has been noted before site-occupancy. For example, forestry solutions should involve both genetics and intensive silviculture management practices to produce greater survival and shorter production rotations to reduce this risk of climatic exposure and enriched competitional stress.

Thermal stress episodes were also analyzed in combination with moisture stress patterns. In this case, moisture stress is defined by the total water deficiency by soil type (MacIver 1988).

Although, thermal stress is the primary variable, incremental biological slowdowns were experienced during coincident periods of moisture stress. Again moisture thresholds and range conditions were derived from the water deficiency versus Specific Volume Increment (SVI) relationships.

The integrated effects of both thermal and moisture stress are demonstrated in the nomogram for mean volume production by 17 yr in jack pine stands on medium to fine sand soils in Figure 4.

The temporal analysis identifies the comparative level of productivity directly related to both atmospheric thermal stress and moisture stress conditions. The "non-stress" thresholds and adjacent interval represent clustered jack pine spatial distributions on medium to fine sand sites. For comparison to this standard, the excess temperatures (high temperature stress) in the Sudbury areas, or the excess precipitation (high moisture stress) in the Cochrane areas of Ontario will result in low levels of productivity for jack pine. In the former case, careful topographic-soil selection could improve production, whereas the excess of precipitation in Cochrane far exceeds site selection limits thereby forcing the manager into intensive mechanical drainage remedial actions.

Provisional spatial mapping of the productivity zones for jack pine and black spruce are presented in Figures 5 and 6. Significant productivity changes can be expected from one region to the next (50% cumulative mean volume differences at 20 yr). In addition, over short distances, regions can change from high to low with a distinct compression of the intermediate productivity region. This occurs principally when crossing the southern boundary of the Boreal Zone for both jack pine and black spruce. This is explained in further detail in MacIver and Karsh (1988).

The patterning of the productivity regions highlights the dominance of continental air masses in the northwestern sections of Ontario, whereas the northern and northeast sectors are influenced by southerly frontal intrusions with significant modification by the Great Lakes, especially Lake Superior. Because of the dynamic nature of this atmospheric stress, yearly fluctuations can be expected to significantly influence forest management practices. For example, given the biological threshold and ranges associated with regions of high productivity, risk analysis for jack pine demonstrates a greater than 60% probability that minimum stress conditions will occur in April at Kirkland Lake, Ontario. In other words, silviculture planting of the new forest should be scheduled to take advantage of these nonstress thermal conditions for these soil conditions. Delays will result in incremental thermal stress usually accompanied by an increased probability of coincident moisture stress resulting in significant physiological stress.

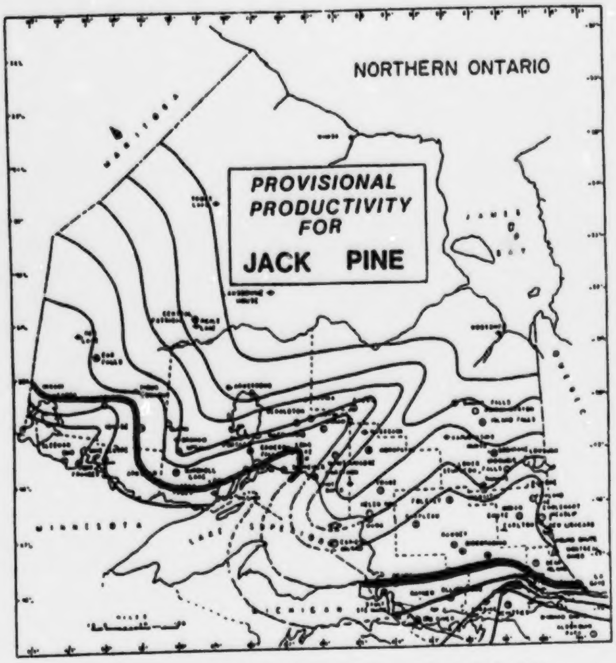

FIG. 5. Provisional productivity map for jack pine.

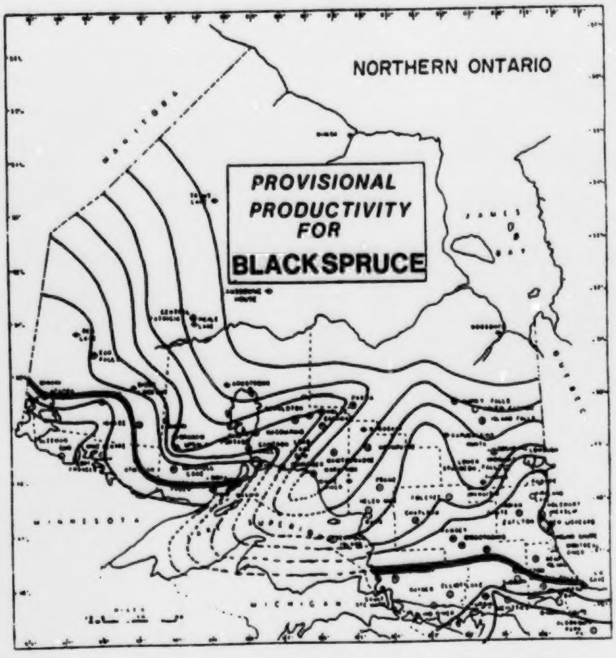

FIG. 6. Provisional productivity map for black spruce.

Summary

This improved understanding and forecasting of the temporal and spatial forest productivity responses as a function of the species-spacing, soil, and climatic interactions should be "in sync" with forest management activities. Harvest schedules, storeability, silviculture prescriptions, tending prescriptions should be timed to the current status of the biological population within specific regions by species. Documenting standard forest growth and development patterns for "healthy" forest stands by region allows for the diagnosis of departures from the expected, identification of the possible causative agent, followed by the appropriate remedial management action. For example, given the development stage of the current thermal stress period, thinning actions are currently recommended in Ontario to optimize subsequent survivor recovery.

Thermal stress in the new forest is a reality and a primary influence compared to moisture stress in the boreal regions of Ontario. To accomplish these respective scales of diagnosis, forest growth and development data must be sensitive to the biological processes and consistent with the required precision for analytical forecasting. This task required the development of the Tree Ring Increment Measuring (TRIM) System, unit area mapping of all species by unit area, replicated destructively sampled plots per stand, and within-tree sampling intensities which document the radial and longitudinal patterns of growth.

The assessment of the impact of climate and monitoring the severity of the atmospheric stress events should be an integral part of operational forest management planning and forecasting activities.

Acknowledgments

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Modeling Soil Water Availability for Seedling Establishment

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Abstract

Soil moisture limits reforestation success in many areas of British Columbia. A water balance model is described that has the potential to allow estimation of water restrictions to tree seedlings and assessment of the length of the planting window. The model requires a minimal amount of site and weather data. Evapotranspiration is calculated as the lesser of energy and soil-limited rates. The atmospheric demand depends on solar radiation, air temperature, and vegetation cover. The soil-limited rate depends on the variation in soil water potential and root density with depth. The multilayered root zone allows estimation of drainage. Sensitivity tests are presented along with results from a comparison with field data. How the model could be used in forest operations and the problems to be met in this situation are discussed.

Résumé

Le succès de la création de forêts est limité par l'humidité du sol à de nombreux endroits en Colombie-Britannique. On décrit un modèle de bilan hydrique qui pourrait permettre l'estimation des restrictions d'eau dans le cas de jeunes plants d'arbres ainsi que l'évaluation de la durée de la fenêtre de plantage. Le modèle ne nécessite qu'une quantité minimale de données sur la météorologie et sur le terrain. L'évapotranspiration est calculée comme la moindre des valeurs limitées par l'énergie et le sol. La demande atmosphérique dépend du rayonnement solaire, de la température de l'air et du couvert végétal. La valeur limitée par le sol dépend de la variation des ressources en eau potentielles et de la densité des racines avec la profondeur. La zone d'enracinement à plusieurs couches permet l'estimation du drainage. On présente des essais de vulnérabilité ainsi que les résultats d'une comparaison avec les données sur le terrain. On examine comment le modèle pourrait être utilisé pour les activités forestières, ainsi que les problèmes qui surviennent dans ce contexte.

Introduction

A lack of sufficient soil moisture to meet atmospheric evaporative demand is thought to be a factor limiting the survival of planted seedlings at many sites. Foresters have tried to avoid this problem by planting immediately after spring snowmelt, when soils are moist and evaporative demand may be low, thus allowing seedling establishment before droughty conditions occur. When this is not feasible, such as high elevation sites where the snow does not melt until midsummer, a second planting window in the fall may be used, when evaporative demand is again low and the soil is still warm.

Since all sites cannot be planted at once, the soil will be drying as the spring planting season progresses. Thus, the forester needs to know when it is no longer safe to plant because the soil is too dry, or, what is the likelihood that the soil may become too dry before the seedling has become established. In the case of fall planting, the forester needs to know whether the soil has moistened sufficiently after summer drying to allow planting. This information could be determined by field measurement and/or by a calculation procedure. Presently, foresters rely on experience and on-site assessment. However, this only gives the present status of the soil, and does not allow the estimation of how long sufficient water will remain in the soil. In the early part of the spring planting season this may not be a problem. However, later in the season this may mean that the forester plays safe and may miss acceptable planting time, or gamble and plant too late. Since the British Columbia Forest Service is attempting to increase the number of seedlings planted each year we must make full use of the planting window. Consequently, we need to have techniques to allow the forester to determine site moisture conditions and the planting window. Furthermore, a knowledge of how site moisture conditions vary from year-to-year would be useful in flagging possible problem sites. This could aid species and stock type selection, scheduling of operations, and a better estimate of regeneration success.

In this paper we describe a water balance model to produce information that could be useful for operational planting programs. The model is tested on a dry site and sensitivity of the model to various parameters is described. How the model could be used and the problems to be overcome in using the model in an operational environment are discussed.

Modeling the Water Balance

Many models for simulating the root zone water balance have been documented in the literature (Spittlehouse and Black, 1981a, 1984). A variety of equations for calculating water fluxes in the atmosphere and soil has been used. A problem with many of these equations is that they require a large amount of weather, vegetation, and site data to give reliable results. Such equations are useful for theoretical or analytical work but are of limited use in many forest situations where data are limited, and where the model may be used to produce information on which to make operational decisions. Other equations that require minimal input data are often overly simplistic and may not be reliable outside the area and conditions for which they were calibrated. We have attempted to produce a model that explicitly deals with as many of the components of the soil water balance as possible so that the model could be used at several sites without recalibration, but does not have excessive data requirements. The model draws on several methodologies

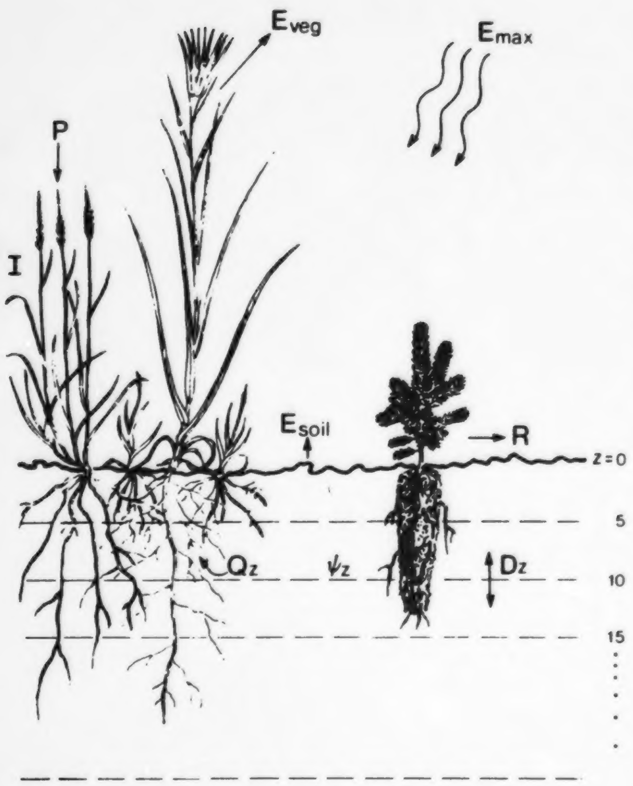

FIG. 1. Schematic of the components of the water balance model. Symbols are explained in the text.

for water balance simulation reported in the literature. Selection was based on the context of, and the data available for, the proposed uses of the model. The method of interpreting model output has not been reported elsewhere. The model and methods of interpretation are presently being tested and improved.

A certain amount of site data are required for any reliable information to be generated by a simulation. The model contains several default values to allow the simulation of the water balance at sites with little information but there is an accompanying degradation in the level of reliability. Table 1 lists the information required by the model, stratified as necessary, desirable, and optional. A schematic representation of the model is presented in Figure 1. There are two above-ground components. The first deals with the simulation of evaporative demand and the calculation of rainfall interception. The second deals with the calculation of actual evaporation and transpiration. The below-ground section deals with drainage between layers and out of the root zone, and the uptake of water by the vegetation. Information from this section is utilized in determining the availability of water to the seedlings. The above-ground component of the site is considered as a single layer. In clearcuts, the vegetation may not fully exploit the root zone. Further, the area of interest for seedlings is the top 0.3 m of the soil. Thus, the model has a multilayered root zone. This also facilitates the calculation of drainage and the determination of water table depth.

The water balance equation for the surface layer is

$$W_{1,i} = W_{1,i\text{-}1} + (P\text{-}I)_i - E_S - D_{1,i} - Q_{1,i} - R_t \tag{1}$$

and for the other layers is

$$W_{z,i} = W_{z,i\text{-}1} - Q_{z,i} + D_{z\text{-}1,i} - D_{z,i} \tag{2}$$

Here, $W_{z,i}$ is the water content (mm) of layer z at time i, P is rainfall (mm), I is rainfall intercepted by the foliage (mm), E_S is soil surface evaporation (mm), D is drainage of water from or into a layer (mm) from the adjacent layers, Q is the uptake of water from a layer by the vegetation (mm), and R is surface runoff (mm). Equations 1 and 2 are solved simultaneously for each layer at each time step. The time step and the depth of the soil layer are input variables. They are chosen as a compromise between stability in the drainage calculations, simulation time, and site information. The weather information used by the model is provided on a daily time step and is interpolated to match the simulation time step.

EVAPOTRANSPIRATION MODEL

The Penman–Monteith equation has been successfully used in several studies to model evapotranspiration from plants and the soil surface (Running 1984, Shuttleworth and Wallace 1985, Lascano and van Bavel 1986, Kelliher et al. 1986). However, the need for wind speed data and stomatal conductance and soil surface conductance characteristics means that this equation is not suitable for the operational type of model required here. Instead, the approach chosen calculates evapotranspiration as the lesser of energy and soil-limited rates (Spittlehouse and Black 1981b, 1984; Spittlehouse 1985). As with any model, this method requires parameters to convert demand and availability of water into actual evapotranspiration. However, few parameters are required and information in the literature suggests that the values of these parameters are conservative. The evapotranspiration component of the model works on a 24-h time step. The amount of water to be removed from the soil is partitioned between the time steps for the daylight hours.

The net radiative energy at the surface represents the atmospheric demand for moisture. The calculation of net radiation at the surface is described later. The energy-limited transpiration rate (E_{max}mm d^{-1}) for dry foliage (E_{maxV}) or the soil surface (E_{maxS}) is calculated using

$$E_{max} = \alpha \, (s/[(s+\gamma) \, L\rho_w]) \, R_n \tag{3}$$

where α is an empirically derived parameter (dimensionless), s, γ and L, are the slope of the saturated vapor pressure curve (kPa C^{-1}), the psychrometric constant (kPa^{-1}), and the latent heat of vaporization of water (MJ kg^{-1}), respectively, calculated at the daily mean air temperature, ρ_w is the density of water kg m^{-3}) and R is the 24-h net radiation (MJ m^{-2} d^{-1}). The daily value of E_{max} is partitioned into each time step for the daylight hours assuming a half sine distribution. Seedling transpiration is not calculated in the model. Measurements of transpiration from 1- or 2-yr-old seedlings indicate that the small amount of water they remove has a negligible effect on the water balance of a layer (Livingston 1986). This is a result of the low leaf area of

TABLE 1. Information required by the model. a = Necessary, b = preferable, and c = optional.

Site location	Soil	Vegetation	Weather data
(a) Latitude Longitude Elevation Slope Aspect	Texture Coarse fragments Bulk density Drainage class or soil moisture regime	Species % cover Root zone depth	Daily rainfall, maximum air temperature, & minimum air temperature for a "nearby" weather station
(b)	Items in (a) as a function of depth Soil retention & hydraulic cond. characteristics	Root density or root abundance with depth	Sunshine from a "nearby" weather station
(c) Topographic shading		Leaf area index	On-site rainfall and temperature Solar radiation from a "nearby" weather station

the seedling per unit ground area. There may be localized depletion around the roots of the seedlings. However, this should be small and, in general, the seedling will respond to the water balance of the layer, a function of the transpiration of the surrounding vegetation and soil surface evaporation.

Water is extracted from the surface layer (litter or soil) by surface evaporation and by plant roots if they are present. The soil-limited surface rate (E_{SS}, mm d^{-1}) is calculated following Rowse and Stone (1978), that is,

$$E_{SS} = k_{1,i}(\psi_{S1,i} - \psi_A) / (0.5\ Z) \qquad (4)$$

where k is the hydraulic conductivity (mm d^{-1}) at the bulk water potential (ψ_S, mm water) of the surface layer, ψ_A is the air dry water potential, and Z is the thickness of the layer (mm). When soil water potential reaches -0.6 MPa, the value of k is not reduced further. This is to allow for the contribution of vapor flow to water movement. Equation 4 estimates the water flow at a depth of $0.5Z$ rather than the surface. This approach assumes that mulching due to the drying of the surface layer takes place over the depth of a whole layer. Equation 4 gives E_{SS} is mm d^{-1}, and is partitioned between the time steps of the simulation.

The actual surface evaporation rate (E_S) is given by

$$E_S = \text{the lesser of } E_{\max S} \text{ and } E_{SS} \qquad (5)$$

where $E_{\max S}$ is calculated from equation 3 using R_n reaching the soil surface (R_{nS}) (Tanner and Jury 1976). R_{nS} is calculated using Beers Law (Jarvis et al. 1976), that is,

$$R_{nS} = R_n \exp(-\eta \mathrm{LAI}) \qquad (6)$$

where η is the extinction coefficient (dimensionless) and percent cover is converted to LAI. R_{nS} is reduced by 30%, to account for the soil heat flux, when calculating $E_{\max S}$.

The soil-limited plant extraction rate for a layer z (E_{pSz} mm d^{-1}) depends on the soil water potential of the layer, the soil hydraulic properties, and the amount of root present (Taylor and Klepper 1975, Rowse et al. 1978, Federer 1979), that is,

$$E_{pSz} = Z\ L_z\ (\psi_{Sz,i} - \psi_P)/(R_{Sz,i} + Rp) \qquad (7)$$

where L is root density (mm mm^{-3}), ψ_p is the plant water potential (mm water), and R_S and Rp are soil and plant resistances to water flow (d mm^{-1}). R_S is calculated using the Gardner (1960) model, that is,

$$R_{Sz} = 1n(1/r_r^2\pi\ L_z)/4\pi\ k_z \qquad (8)$$

k is the hydraulic conductivity of the soil (mm d^{-1}) at the water potential of the layer and r_r is the mean root radius (mm). R_S is not too sensitive to the size of r_r and L. If L is not available, default values based on root abundance are used. Federer (1979) shows that equation 7 is similar to the soil-limited transpiration rate used by Spittlehouse and Black (1981b, 1984) and Spittlehouse (1985) where the size of their "b" parameter will depend on the root density and the soil and plant resistances. In equation 7 it is assumed that root and leaf water potentials are the same, that is, xylem resistance is small. This is probably a reasonable assumption for the low-growing vegetation considered here. The uncertainty in the value used for Rp is of the size of the xylem resistance. Hydraulic conductivity and root resistance vary with the temperature due to variation in the viscosity of water. Other possible low temperature-induced reductions in Rp due to metabolic effects (Krammer 1983) are not considered. The model determines k, or has Rp as an input, for a reference temperature of 20°C and then adjusts them based on the actual temperature of the layer. Note that k decreases and Rp increases as temperature decreases. Soil temperature is obtained from a soil temperature model, described later, running in conjunction with the water balance model.

The actual amount of water removed from a layer depends on the ratio of demand to availability. The values of E_{Sz} for each layer are summed over the root zones (E_{pS}, total) and the actual amount of water removed by transpiration in a layer (Q_z) calculated from

$$Q_z = \text{lesser of } [(E_{\max V}/E_{pS,}\ \text{total})\ {*}E_{pS,z}] \text{ and } E_{pS,z} \qquad (9)$$

where $E_{\max V}$ is calculated from equation 3 using R_n reduced by the amount reaching the soil surface, that is, $R_{nV} = (R_n - R_{nS})$.

INTERCEPTION OF RAINFALL

Rainfall interception (I) is calculated using (Spittlehouse and Black 1984)

$$I = 0.08\ \mathrm{LAI}\ P^{0.6} \qquad (10)$$

where P is the daily rainfall (mm d^{-1}) and LAI is the leaf area index (the percent cover being converted to an LAI). This equation was derived for a Douglas-fir stand and will give only an approximation to I since values of the parameters in equation 10 will depend on the architecture of the vegetation canopy. However, the equation gives values for I similar to those reported elsewhere in the literature, for example, Rutter (1975), Wallis et al. (1983). For low-growing vegetation the intercepted water is assumed to evaporate at the energy-limited rate (Calder 1979, Wallis et al. 1983, McNaughton and Jarvis 1983). The value of E_{max} for the canopy is reduced by I on rainy days before being used in the calculation of transpiration.

INFILTRATION AND RUNOFF

In the present model, all rain reaching the soil surface is assumed to infiltrate into the soil. The daily value of $(P - I)$ is divided into 2.0-mm portions and input to the soil each time step starting at the beginning of a day. Since only daily rainfall is available it is not possible to determine whether the rainfall rate at any time was greater than the infiltrability of the soil surface. Philip's (1957) equation will be used to consider this phenomena if short-term rainfall data are available. Runoff or ponding can also occur when the water table reaches the soil surface. This situation is dealt with in the model through the water table drainage calculation procedure.

DRAINAGE

Drainage from a layer (D_z mm per time step) to the one below it is calculated using the equation for Darcy flow, that is,

$$D_z = -k_z (\psi_{Sz} - \psi_{Sz+1})/Z \qquad (11)$$

where k is the hydraulic conductivity (millimetres per time step) of the layer at the average soil water potential of the two layers. Hydraulic conductivity and soil water retention are calculated following Campbell (1974, 1985), that is,

$$\psi_S = \psi_e(\theta / \theta_S)^{-m} \qquad (12a)$$

for ψ_S less than the air entry value (ψ_e)

$$k = k_S (\theta / \theta_S)^n \qquad (12b)$$

and for ψ_S equal to or greater than ψ_e

$$k = k_S \qquad (12c)$$

where θ and θ_S are the actual and saturated volumetric soil water content, respectively (m^3 water/m^3 soil), ψ_e is the air entry potential (MPa), k_S is the saturated hydraulic conductivity (mm d^{-1}), and m and n are empirical constants. If these characteristics are not supplied, default values that are a function of soil texture (Clapp and Hornberger 1978) are used. The retention and hydraulic conductivity relationships are corrected for bulk density (Campbell 1985) and coarse fragment content.

The drainage from each layer for one time step is determined simultaneously using a one-dimensional finite difference model solved with the Crank–Nicholson approximation (Remson et al. 1971). The use of equal size layers throughout the profile simplifies the solution of the tridiagonal matrix and reduces computing time. A discontinuity occurs in the equations at a water table, and this can cause an instability in the solution. Thus, this procedure takes place only for layers above the layer(s) containing the water table, or above and below a perched water table. The bottom boundary condition in a nonwater-table situation is obtained by assuming the bottom layer drains through a unity gradient to a potential of -0.01 MPa and then seals. When there is a water table at the base of the profile it drains at a value less than or equal to k_S depending on the drainage class or soil moisture regime of the site. The rate of movement of water within, and upward from, the water table is equal to the saturated hydraulic conductivity of the layer.

SOIL TEMPERATURE

A model to estimate soil temperature accompanies the water balance model. However, heat and water fluxes are not coupled. The model numerically solves the heat flow equations (Campbell 1985) for each depth using the Crank–Nicholson approximation (Remson et al. 1971). The bottom boundary condition at 1.5 m is a fixed temperature of 5°C. The surface boundary condition is the air temperature. This assumption is only valid for a well-shaded surface (Stathers et al. 1985). However, temperature data are mainly used to correct soil hydraulic conductivity and plant resistance, and the effect of this simplification is minor. The air temperature is assumed to vary as a sine wave using the maximum and minimum temperatures to define the amplitude and assuming the minimum occurs at dawn and the maximum occurs at 1600 solar time. The times of sunrise and sunset are calculated from the date. The soil texture data and the modeled soil water content are used to calculate the required thermal properties (Monteith 1973, Campbell 1985).

WEATHER DATA

Net radiation is calculated on a 24-h basis using solar radiation and air temperature (Spittlehouse and Black 1981b, Spittlehouse 1985), that is,

$$Rn = (1\text{-}a)\, K\downarrow + L^* \qquad (13a)$$

$$L^* = (0.1 + 0.9\, K\downarrow/K\downarrow_{max})\, (\varepsilon_a - \varepsilon_v)\, 4.9 \bullet 10^{-9}\, T^4 \qquad (13b)$$

$$\varepsilon_a = 1 - (0.261 \exp[-7.77E\text{-}4 * (273\text{-}T)^2]) \qquad (13c)$$

where a is the reflectivity of the surface (dimensionless), $K\downarrow$ is the solar radiation (MJ m^{-2} d^{-1}) corrected for slope angle and aspect, L^* is the long wave radiative balance, $K\downarrow_{max}$ is the clear sky value of solar radiation (MJ m^{-2} d^{-1}) for the day obtained from the solar record or calculated (see below), ε_a is the apparent emissivity of the sky calculated from air temperature (T in Kelvin) (Aase and Idso 1978) and ε_v is the emissivity of the vegetation taken to be 0.96. If sunshine hours are available instead of solar radiation, then solar radiation is calculated using the method of Hay (1979). If there are no sunshine or solar data, then a calculated value of clear sky radiation is determined following Davies and Hay (1980) and Hay and Davies (1980). This value is a function of elevation, aspect, slope angle, air temperature, and an assumed water vapor content of the air. (The reader is referred to the references for details of the method.) Clear sky solar radiation is determined on a half hourly basis and summed to give a daily total. Actual solar radiation is estimated by adjusting for cloud cover. This is achieved by multiplying clear sky solar radiation by the ratio of the difference between the maximum and minimum air temperature of the day to the value of the maximum difference for the month.

Air temperature and rainfall can be adjusted for elevation where necessary using locally derived calibrations.

PLANTING WINDOW ASSESSMENT

The planting window concept is based on the assumption that after planting, a seedling requires good soil water conditions for a certain length of time to allow establishment. The seedling must reach a physiological state that allows it to withstand subsequent harsh conditions such as a summer drought (after spring planting), or the winter cold (after fall planting). In both cases the seedling needs time to grow roots and to harden off, that is, osmotically adjust. Requirements vary between species and are not well known. In this study, a period of 4 wk with a soil water potential in the top 0.15 m of soil continually greater than -0.1 MPa (-1 bar) is used to define the planting window; that is, if at the present time, there will not be 4 more weeks with the surface water potential >-0.1 MPa, then the planting window is considered to be closed. Several studies have indicated that root and shoot growth will have been substantially reduced by this soil water potential. The model also allows the assessment of other environmental conditions that might influence the response of the seedling, for example, low temperature, and dry soil drying may become too severe. When estimating the effect of the soil water regime on the seedling it is assumed that the water potential around the roots of the seedling is equal to that of the layer.

Testing the Model

Part of the model was originally developed and tested on mature stands of trees in the Interior of British Columbia. The model simulations compared with measured soil water content were encouraging, although calibration of root uptake functions was required. These simulations also indicated which parameters were most important. This information helped in applying the model to a backlog clearcut in the Interior of British Columbia.

SITE DESCRIPTION

The data used to test the model are from a study on the effect of pine grass (*Calamagrostis rubescens,* Bulk.) competition on the survival and growth of planted Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) seedlings. The Em Fire site is a 57-ha clearcut about 45 km south of Williams Lake. It is located on the Frazer Plateau in gently undulating terrain, 51° 40′N and 121° 57′ W at 1150 m above sea level on an 8% westerly facing slope. The nearest long-term climate record (Dog Creek) indicates a yearly average precipitation of 388 mm of which about 200 mm fall between May and September. These values can vary by ±80%. Winter snowpack is shallow. Daily average air temperature ranges from 16°C in summer to -10°C in winter. Maximum summer air temperature can reach 34°C, minimum winter air temperatures can reach -40°C and no month can be considered frost free. On average there are 1306 growing degree-days per year (5°C base). The site was logged in 1972 and burned. There has been negligible regeneration of trees. The vegetation is mainly pine grass with a few other herbs, shrubs, and mosses. The site is classified as IDFb, *Calamagrostis-Linnaea* ecosystem association (Annas and Coupe 1979). The soil is a silt loam Orthic Grey Luvisol (see Table 2).

TABLE 2. Site and soil characteristics.

(a) Site
LAI = 1.0 used in equations 6 and 10; 51° 40′N, 121° 57′W
Slope = 8%, facing west, elevation = 1150 m

(b) Soil

Depth (m)	Texture	Coarse frag. (% vol)	Bulk density (mg m^{-3})	Root abund.	Parameters					
					θ_s	ψ_e (MPa)	k_s (mm d^{-1})	M	N	L (mm mm^{-3})
0 - 0.1	*SiL**	8	1.33	Very High	0.495	0.002	15	5.00	13.0	0.005
0.1 - 0.3	*L*	25	1.34	High	0.489	0.003	187	6.10	15.2	0.003
0.3 - 0.5	*L*	30	1.51	High	0.477	0.0003	4	6.89	16.8	0.003
0.5 - 0.7	*SL*	45	1.77	High	0.355	0.006	12	4.83	12.7	0.003
0.7 - 1.0	*SL*	45	1.86	None	0.328	0.011	16	4.87	12.7	0.0

*3% organic matter in 0 to 0.05-m layer.

Two treatments are considered here, pine grass present, and pine grass removed by hand scalping and later herbiciding the scalped area to prevent regrowth. Above-ground weather data used are daily rainfall. The data were collected by spot reading the sensors every 10 s with a Campbell Scientific 21X datalogger. For the few days when data were not available, air temperature and rainfall data from Lac La Hache, about 30 km east, were used with adjustments indicated by comparing concurrent data. Solar radiation was calculated from estimates of clear sky radiation at the site and cloudiness at Williams Lake. The data logger was also used to measure soil temperature (5 and 150 mm) and soil moisture blocks (50, 150, and 300 mm) in each treatment. Manual measurements of other moisture blocks, gravimetric sampling, and a neutron probe were used to assess variability over the site.

SELECTION OF PARAMETER VALUES

An important part of any model are the values of the parameters in the equations. Since we cannot expect to have values for most situations we must assume that the values can be estimated with acceptable accuracy from the site information and from the literature. Several of the required parameters were measured at the test site. These were slope, aspect, elevation, leaf area index, the soil water retention properties, soil depth, and root abundance. This last parameter was converted to root density (Table 2). The other parameters were estimated from information in the literature and experience. The values used are presented in Table 3 and discussed later.

Published values of α appear to range from about 0.7 to 1.3 (Spittlehouse and Black 1981b, Brutsaert 1982). Agricultural crops, grass, and wet bare soil appear to be at the high end of the range with conifers at the lower end. The higher end is favored here since most competing vegetation is broad-leaved, low-growing brush, or grass.

Values for Rp reported in the literature range 10^3 to 10^6 d mm^{-1} (Taylor and Klepper 1975, Newman 1976, Rowse et al. 1978, Nnyamah et. al. 1978, Federer 1979). Some results suggest that Rp varies with soil or plant water potential (Blizzard and Boyer 1980). However, this variation is within the range of Rp noted previously. Since values for the vegetation considered here are not known, Rp for the 20°C reference temperature was fixed at a constant value in the midrange of the published values. Similarly, mean root radius is based on values in the literature.

TABLE 3. Values of parameters.

Parameter	Value	Equation
α	1.26	3
ψ_A	-10 MPa	4
Z	50 mm	4, 7, 11
η	0.23	6
Rp	10^4 d mm^{-1}	7
r_r	1.0 mm	8
ψ_p	-1.5 MPa	7
L	see Table 2	7, 8
a	0.2	13a
ε_v	0.96	13b
Time step	30 min	

A plant water potential (ψ_p) of -1.5 MPa is based on data in the literature and some midday measurements at the site (Nicholson unpublished data). This value varies through the day and assuming it to apply for all of the daytime will overestimate the soil-limited transpiration rate. The value used for ψ_A was assumed to be the value for air-dry soil. The albedo (a) is based on values reported elsewhere for a prairie grass (Ripley and Redmann 1976) and light-colored soil (Monteith 1973).

Results and Discussion

Weather data for 1985 used in the model are illustrated in Figure 2. Spring 1985 was relatively dry, followed by a wet June and then a hot, dry July and August. At Williams Lake, March to May rainfall was 57% of the average, June 139% of average, and July and August 34% of average. July mean temperature was 2.5°C above average. At the site, maximum daily air temperatures were frequently over 25°C, with minimums down to 5°C. The maximum daily vapor pressure deficit was frequently greater than 2.5 kPa and occasionally greater than 3 kPa. The atmospheric evaporative demand was between 5 and 7 mm d^{-1} in midsummer.

The model simulations presented will focus on the top 0.2 m of the soil since this is where the newly planted seedling's roots are located. Figure 3a shows the simulated soil water potential in the 0 to 0.1-m layer of grass and bare soil treatments. Drying of the surface layer occurred in mid-May, immediately after planting the seedlings. There was some rain at the end of May but this was rapidly used up and the soil dried to less than -0.1 MPa. However, in the 0.1 to 0.2-m layer (Fig. 3b) of the bare soil treatment strong drying in the surface layer acted as a barrier to high water loss with the result that the lower layers stayed moist (ψ_S > -0.05 MPa). In the grass treatment, the grass continued to extract water from the lower layers as the surface dried out, rapidly drying the 0.1 to 0.2-m layer to -1.1 MPa by late August. Lower layers in the grass treatment dried out at a similar rate to this layer. In the bare soil case the model calculated negligible loss of water from below the 0.2-m depth.

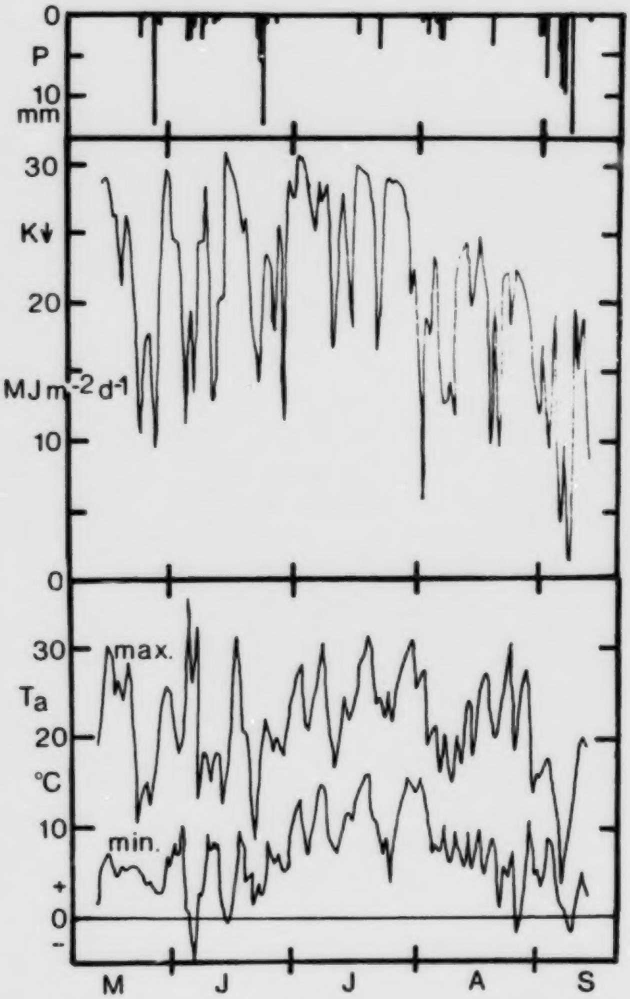

FIG. 2. Weather data for May 13 to September 15, 1985 used in the simulations. P = rainfall, K↓ = solar radiation, T_a = maximum or minimum air temperature.

Measured soil water status varied greatly between the replicate measurement locations. This is probably a result of the variation in hydrologic properties and plant density across the site. The simulated data shows the same trend as the measured data. The grass treatment simulation agrees with the wetter sets of measurements. Most of the measurements for the bare soil are drier than the simulated values. In this case, the measurements indicated drying to below 0.3 m which suggests that there were roots beneath the bare surface from the grass outside the treatment area. This is possible since only small patches (0.3 m square) had the turf removed and herbicide application did not take place until midsummer, too late to have had a major impact on the grass. Figure 4 shows the effect of various root densities on simulated soil water potential. Even a small amount of root can have a major impact on the water availability at a dry site. The simulations suggest the root density needs to be known to within an order of magnitude.

In general, there is an underestimation in drying of the surface layer indicating improvements to the model are required. The first is that ψ_A should probably be -100 MPa. Second, as the soil dries vapor flow becomes important (Campbell 1985). An attempt to correct this was made by keeping the hydraulic conductivity constant when ψ_S was less than -0.6 MPa. The use of thinner layers near the sur-

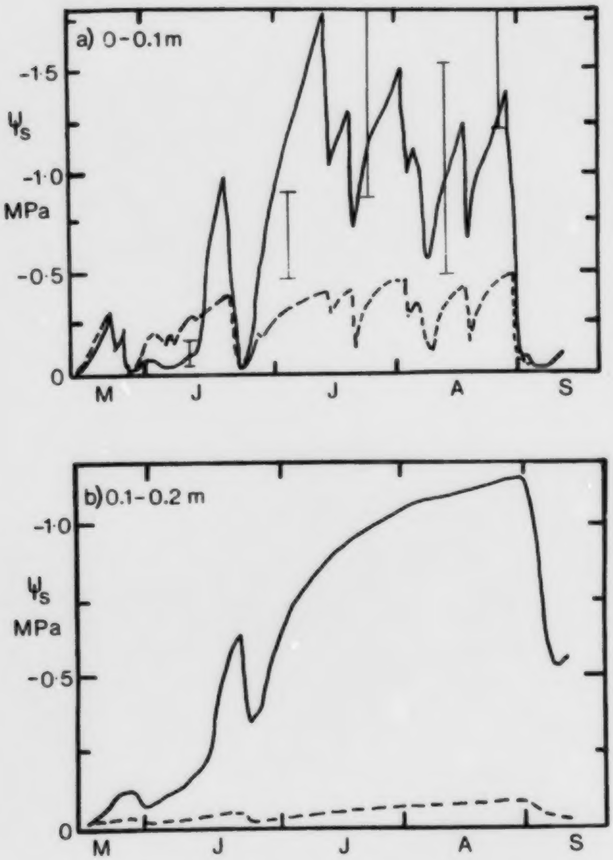

FIG. 3. Simulated soil water potential of (a) the 0 to 0.1-m layer and (b) the 0.1 to 0.2-m layer. Solid line is the grass treatment and the dashed line is the bare soil treatment. Range of measured values for the 0 to 0.1-m layer of the grass treatment shown.

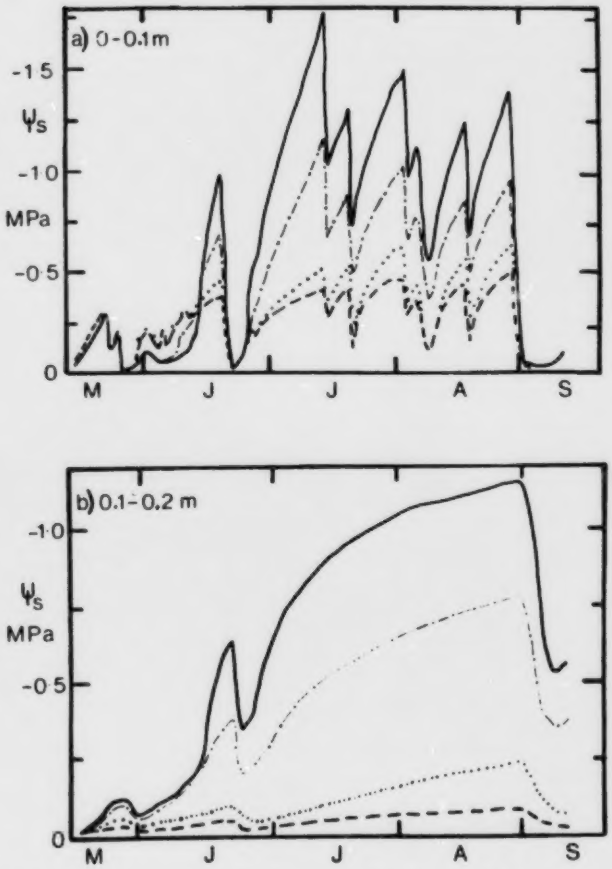

FIG. 4. Simulated soil water potential of (a) the 0 to 0.1-m layer and (b) the 0.1 to 0.2-m layer for four values of root density. Solid line = 0.005 mm mm^{-3}, dashed and dotted line = 0.001 mm mm^{-3}, dotted line = 0.0001 mm mm^{-3} and dashed line = no roots.

face could improve matters. However, this is a simple model and it can be improved only so far. Further research is required here.

The sensitivity to the plant resistance *(Rp)* is shown in Figure 5. Varying the size of *Rp* by two orders of magnitude (the range of values in the literature) does not have a large effect on the water balance. The main difference is that the soil does not get as dry in midsummer when the higher value is used. Thus to estimate the planting window the order of magnitude estimate used appears to be reasonable. Since the root density and root resistance appear together in equation 7, it is not possible to estimate the correct value of *Rp* without measurements of *L*.

Apparently the seedling planting window had almost ended at the time the seedlings were planted. The seedling plugs were about 130 mm long. Thus, they probably had access to the wetter 0.1 to 0.2-m layer and this may have helped their survival. This layer could be important to seedling survival since it would be insulated from large water losses by surface mulching. However, only a few roots from competing plants are needed for the loss of this reserve during a dry period. Seedling transpiration, plant water potential, and survival data (Nicholson unpublished data) for the treated area indicate that the seedlings suffered severe water stress. There may also have been heat stress due to the high radiation load and high near-surface air and soil temperatures.

Using the Model

The model simulations are by no means exact. However, they do indicate the trend in soil drying, and illustrate what parameters are important in the availability of water to the seedling. This is the first pass at the data in an ongoing project. Tests for other sites and the improvements that are being considered should increase the reliability of the model. Thus, it is pertinent to consider how the model could be used in an operational setting.

WHAT COULD BE DONE WITH THE MODEL?

The model is a good teaching tool. It illustrates how a site can dry out and what factors such as soil water holding capacity and amount of competing vegetation are important in soil drying. This shows how to use information collected on preharvest assessments and could aid in the determination of site treatment prescriptions.

It would also be advantageous if the model could be used to help make actual planting decisions. This question can be divided into two classes of tasks. The first is planning

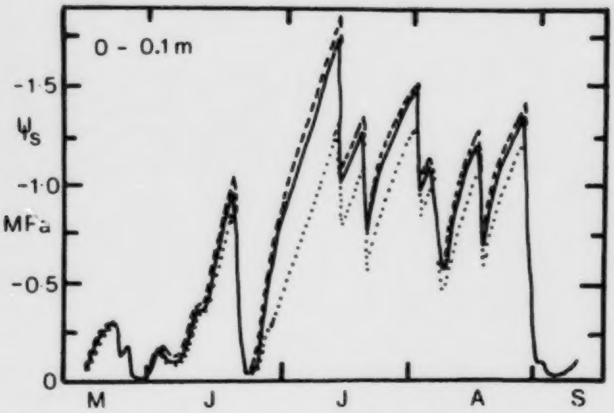

FIG. 5. Simulated soil water potential of the 0 to 0.1-m layer for the grass treatment for three values of root resistance *(Rp)*. Dashed line = 10^3 d mm^{-3} d mm^{-1}, solid line = 10^4 d mm^{-1} and dotted line 10^5 d mm^{-1}.

and the second is making real-time decisions. In the latter case, current weather data would be used along with appropriate site data to estimate the current soil moisture conditions and allow the estimation of the length of time the remaining reserves may last without rain. The silviculturalist would then have to consider the weather forecast for the next few weeks to decide whether there will be sufficient rain to maintain the surface soil moisture potential above some critical value such as -0.1 MPa. Another option would be to consider the probabilities of how much rain could occur. This would require an a priori analysis of local and regional weather patterns.

The above discussion leads into the task of planning a planting program. In this case, the model would be used before the planting season, (e.g., at the time of preharvest assessment) to indicate the probability of, and time at which, various sites would dry out. The information could be used to rank the various planting sites for the year, and aid the planning of the planting schedule. Several different weather scenarios could be used to consider the range in length of the planting window at various sites. If these results are related to the weather conditions for 20 – 30 yr, we can extend the site assessment. The data could be used to determine the probability of different levels of risk for a site. This is similar to procedures already used in agriculture where the probability of requiring various amounts of irrigation water are determined. This information could be used to guide species and stock type selection.

An example of how the model might be used for planning is presented in Table 4. The first two columns describe five weather regimes and their probability of occurrence. The next three columns list whether there may or may not be a planting window problem at three different sites within the same planting area, under each of five weather regimes. This information would be obtained from model simulations. The difference between sites A, B, and C may be due to a variety of site factors. For example, site parameters such as soil texture or stone content, site treatment (e.g., % removal of vegetation), or variation in rainfall along an elevational gradient. "Y" means no problem, or a long-planting window, and "N" means a short-planting window.

TABLE 4. An example of using the probability of occurrence of various weather regimes, and simulated length of planting window under these regimes for various site conditions, to assess the probability of planting window problems. Y means no problem or long-planting window, N means problem or short-planting window.

Weather regime	% occurrence	Planting window Site A	Site B	Site C
Wet	10	Y	Y	Y
	20	Y	Y	Y N
	30	Y	Y N	N
	30	Y N	N	N
Dry	10	N	N	N N
% time with no problem		60	30	10
% time with major problem		10	40	70

Combining each of these columns with the weather probabilities gives the probability of occurrence of planting window problems at each site. These probabilities could be further modified depending on the reliability of the input data. The information can then be used to flag problem sites and decide which ones should be planted first in the year. It could also indicate that at site A, for example, competition for moisture is not a problem most of the time. This may help decide the type of site preparation that is cost effective in most years. Once the planting season is underway the forester may be able to use Table 4 and the weather forecast to make further decisions, for example, what is the likelihood that this year is the year in which there will be problems at site B.

Other information such as length of drought or degree of dryness could also be presented in a form similar to Table 4. It would be useful to link this information with the ecological classification of the site. Thus, the forester may also be able to get a general idea of site moisture conditions without having to simulate the water balance at every site. Since there are several constraints to planting such as stock type and species availability, order of magnitude information may be adequate for many planting situations.

PROBLEMS TO BE ADDRESSED IN THE OPERATIONAL USE OF THE MODEL

Assuming the model can be shown to be a useful tool in the reforestation process, there are several factors that must be addressed before it could be used. The most important factor is the data required to run the model to produce a reasonable degree of reliability in the predictions. Weather data are often collected at points a long distance from, or at a much lower elevation than, the forest sites being managed. Real-time data are not readily available for most stations in the Atmospheric Environment Service network. It would be very expensive to set up and maintain a system for real-time collection of data on a broad scale. The increase in the size of the fire weather network in British Columbia may partly address this problem. However, real-time data does not help if we wish to assess year-to-year variations. In this situation, historic weather data are required. Thus, there will be a requirement for the interpolation and extrapolating of near surface weather data across the landscape, that is, topoclimatic modeling (Nunez 1980, Taylor and Waite 1980, Running and Hungerford 1983). This is not an easy task because many of the relationships are area specific.

A second aspect of data requirement is the site information. A good preharvest assessment is required to define the soil type and vegetation competition that may occur. Clapp and Hornberger (1978), Campbell (1985), and several others have related soil texture, bulk density, etc., to soil water retention and hydraulic conductivity characteristics. We are building a data base of these soil physical and hydrologic properties for forest soils in British Columbia. Thus, only soil physical characteristics may need to be measured at a site. The plant factors will not be known with a great degree of accuracy. However, parameters in the evapotranspiration equations are relatively conservative. Knowledge of seedling requirements and tolerance to environmental stress is critical. Variations between ecotypes of a species and from species to species is not known in any detail.

A third consideration is who does the computer analysis? Should a computer program be available for use by the district forester? The program would have to have several checks built in to reject unreasonable data. A similar computer program is being tried in the United States. (Warrington and Weatherred 1983). The user inputs site-specific factors such as soil texture, elevation, and map coordinates and the program uses site location to interpolate average weather (climatic) conditions from a reference data-base of climate stations. However, with the topography of British Columbia and the site-specific nature of the coefficients for interpolating variables (e.g., rainfall) with elevation, such an approach is not yet feasible on a large scale. It may be possible to set up the program for a specific area. However, most foresters do not have a forest climatology background and could not be readily trained to use the water balance model. At the moment, regional ecology and silviculture staff in the British Columbia Forest Service, with the help of a consultant, would probably be the most appropriate people to use the model. They have the local knowledge along with some relevant training. The information from the simulations could be used in the ecological guides.

There is a need for a simplified procedure by which a forester could get an order of magnitude, real-time assessment of the planting conditions. We are addressing this problem by developing a set of tables and a "simple" manual calculation procedure.

Once the forester has some idea of the planting conditions he has to be able to use the information. This requires an administrative structure that allows flexibility in allocation and reallocation of resources (planters, machinery, and seedlings) in response to the planting window, within the limitations of species and stock availability.

Conclusions

The water balance model described can produce water depletion patterns that approximate those measured in the field. The model produced the "expected" result of a mulching of the surface layer and the conservation of water below this layer. The surface layer dried out less than was expected. However, we were improving the model, particularly the surface evaporation component. The model will be tested with data for 1986 at the site considered here and at other sites. Research is required to define the variability in the parameters between several sites.

The model has possibilities as a teaching tool and as a tool to aid site assessment and planning the planting schedule. More work is required before the model could be considered reliable enough to aid real-time decision-making. Also, improvements in real-time data collection, topoclimatic modeling, and education of foresters are required. The environmental requirements and limitations of most species and stock types must be defined.

Acknowledgments

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Influence of Prescribed Burning on Seedling Microclimate and Its Potential Significance in Northern Interior British Columbia

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Abstract

Prescribed fire can have beneficial effects on seedling microclimate, but the effective use of fire as a silviculture tool depends not only on increasing our knowledge about microclimate changes and responses by seedlings and competing vegetation but also on delivering information in the form of guidelines appropriate for prescribed fire decision-making. We do not have enough quantitative knowledge about the response of seedlings to changes in microclimate, and field experiments must use a holistic approach incorporating studies on fire impacts, microclimate, nutrients, and seedling response.

Résumé

Les brûlages dirigés peuvent avoir un effet bénéfique sur le microclimat des semis, mais l'utilisation efficace du feu comme outil sylvicole dépend non seulement de l'approfondissement des connaissances sur les changements microclimatiques ainsi que sur les réactions des jeunes plants et des végétaux concurrentiels, mais aussi de la diffusion d'information sous forme de lignes directrices qui facilitent le processus décisionnel dans le secteur du brûlage dirigé. Nous ne possédons pas suffisamment de connaissances quantitatives sur les réactions des jeunes plants aux changements microclimatiques, et les essais sur le terrain doivent comporter une approche holistique incorporant des études sur les impacts d'incendies, le microclimat, les éléments nutritifs et la réaction des semis.

Introduction

The subboreal spruce biogeoclimatic zone in British Columbia (Krajina 1965) is dominated by white spruce (*Picea glauca* (Moench) Voss) and some Engelmann spruce (*Picea engelmannii* Parry) with a significant proportion of lodgepole pine (*Pinus contorta* Dougl.). These are commercially valuable species occupying a significant proportion of the potentially productive land base in British Columbia (Dobbs 1972, Stiell 1976, Kennedy 1984). Following clearcut logging, the dominant silviculture practice in the subboreal spruce zone is fall burning for slash hazard reduction and site preparation, followed by planting of container-grown 1- or 2-yr stock the next spring or early summer. Lodgepole pine is lately being selected for planting as an alternative to white spruce on problem sites due to the increasing economic value of lodgepole pine and its aggressive capability for establishing itself over a wide range of edaphic and climate conditions (Eis 1982, Kennedy 1984).

White spruce does not readily reestablish itself after logging through natural regeneration, so planting after logging is necessary. It is crucial that sites be replanted as soon as possible after logging on moist sites (i.e., Devil's Club and Alluvium) so that seedlings start with and maintain a competitive advantage over invading shrubs and grasses (Eis 1981). Following logging, 6–7 yr elapse before competing vegetation becomes a serious hindrance to regeneration (Eis 1981). Unfortunately, there are large areas in British Columbia which have either not been planted or for which planting has failed. These nonsatisfactory restocked sites (NSR) are a major problem for forest managers in the subboreal spruce zone. Mechanical site preparation is generally used, but several variants and strategic alternatives for site preparation and planting are being investigated for rehabilitating this NSR land. Studies dealing with the effects of mechanical site preparation techniques have been reported at this symposium (McMinn 1988). We have begun a study to examine the effects of using prescribed fire versus mechanical treatments on a backlog NSR site in the subboreal spruce zone (Taylor et al. 1986). Treatments will be applied in the fall of 1987, followed by the planting of white spruce and lodgepole pine seedlings in the spring of 1988. Fire impacts, microclimate, vegetation and nutrient dynamics, and survival and growth of planted seedlings will be monitored in detail until 1990. In this paper we provide an overview of the effects on site microclimate that can be expected to follow from prescribed fire treatments on subboreal spruce sites.

Effects of Burning on Site Microclimate

A prescribed burn usually results in a charred and blackened surface from which the above-ground portions of competing vegetation have been removed, slash partly consumed, and the organic layer reduced to some degree. One would expect substantial changes in microclimate and indeed changes significant to seedlings to occur. Properties of the seedling environment, such as air, surface and soil temperatures, and soil moisture, are the result of energy exchange processes at the surface (Geiger 1965, Campbell 1977). These energy exchange processes are altered by any changes that might occur in the amount of solar radiation that is reflected (albedo), the efficiency with which thermal radiation is emitted (emissivity), and the amount of heat energy that is conducted through the insulating organic layer. Not all the changes are obvious, however, and considerable variation exists between results in the literature. In general, variability in microclimate can be explained largely by the characteristics of the residual organic layer (Fowler 1974).

RADIATION PROPERTIES OF THE SURFACE

Albedo — There is a pronounced decrease in the amount of incoming solar radiation that is reflected by the surface immediately after burning. Before burning, a cleared site will typically have albedos in the range of 10–15% over organic surfaces, and 15–20% over exposed mineral surfaces (Ballard et al. 1977, Fowler 1974, Geiger 1965). On recently burned sites in the subboreal spruce zone during July of

1986, we measured albedos ranging between 3 and 6%. Others have also noted comparably low values (Ballard et al. 1977, Fowler 1974). After several months to more than one growing season, the surface charcoal is translocated deeper into the remaining organic or mineral horizons, vegetation is reestablished, and albedos return to preburn values.

Emissivity — The efficiency with which surfaces covered by vegetation or organic material radiate thermal energy is quite high, typically around 0.97 (Ballard et al. 1977, Gates 1965). Blackened residual organic surfaces will have emissivities exceeding 0.97 (Fowler 1974). However, patches of mineral soil may be exposed and these surfaces have lower emissivities. Thus it is not obvious beforehand what the spatially averaged emissivity across a burned site will be. However, it is unlikely that emissivity will be significantly altered, except on severe burns where emissivities similar to those for bare mineral soil may be more appropriate. For example, Ballard et al. (1977) found no significant difference in emissivity between burned organic, unburned organic, or mineral surfaces.

TEMPERATURES

Surface Temperature — Temperature on the surface of the residual blackened organic layer can be extreme, particularly if the organic layer remains dry. Additional incoming shortwave radiation is absorbed as a consequence of low albedo and is partitioned mostly between longwave radiation and sensible heat transfer to the atmosphere. There is very little additional heat transfer into the soil underneath the dry organic layer. Evaporation is reduced due to the loss of transpiring vegetation and the high resistance of the organic layer to moisture transport.

Very high surface temperatures have been reported on recently burned sites. Viro (1974) reported a typical midafternoon surface temperature of 52.8°C for a burned area compared with 36.0°C at the surface of a nearby unburned clearing for a site in Finland. Hungerford (1980) found that daily maximum surface temperatures were similar for burned and unburned sites, ranging from 50 to 60°C, with one extreme value of 70°C. Maximum temperatures were generally 10°C lower on bare mineral surfaces. Endean and Johnstone (1974) found no marked difference between burned and unburned organic surfaces. Sims (1976) measured summer daily maximum surface temperatures ranging between 57 and 69°C on burned litter compared with 51 to 63°C on bare mineral soil. Lethal temperatures for coniferous seedlings have been cited ranging between 49 and 60°C (Dobbs 1972, Sims 1976, Hungerford 1980). Kayll (1963) stressed the need to consider the length of time that high temperatures are present. Shirley (1936) observed that seedling tops were more resistant to high heat than roots. Seedling temperatures are the result of energy gains and losses from several sources. Seedling temperatures may become high but are not nearly as extreme as surface temperatures would suggest. For example, Ballard et al. (1977) measured maximum surface temperatures of 72, 69, and 63°C associated with seedling cambium temperatures of 47, 47.5, and 44°C over burned, organic, and mineral surfaces, respectively. McMinn (1982) did not observe soil temperatures high enough to be lethal to planted seedlings during 10 yr of trials comparing untreated organic and exposed mineral surfaces in the subboreal spruce zone of British Columbia.

As noted previously, the emissivity of the surface does not change greatly as a consequence of burning. Differences in minimum surface temperature between burned and other site treatments will be due largely to differences in thermal admittance of the surfaces. Thermal admittance is a parameter that indicates how well a material can both conduct and store heat (Cochrane 1969). Because the thermal admittance of an organic layer is only about one-fifth that of bare mineral soil (Ballard et al. 1977), minimum surface temperature will be lower over organic surfaces. Furthermore, minimum temperatures should be slightly lower over unburned versus burned organic surfaces because heat stored in the soil is more readily conducted to the surface through the thinner residual burned organic layer. It follows that one should expect minimum surface temperatures to be lowest on untreated organic surfaces, highest on bare mineral soil, and somewhere in between on burned surfaces. Published data (Feller 1982, Hungerford 1980) support this simple model, but the data and interpretations of the data are highly variable. Usually, differences between burned and unburned organic surfaces are small and insignificant (Viro 1974). The interpretation of results has invariably been complicated by factors such as the presence of slash and stumps, residual vegetation, stand edges, and topography. Geiger (1965) and Hungerford (1980) give excellent examples of the overriding importance of these factors. We conclude that prospects are poor for the development of simple process-based models that can be used to provide useful quantitative predictions of minimum surface temperature.

Soil Temperature — The significance of increased soil temperature depends not only on the amount of change but also on where changes occur relative to the rooting zone, and when they occur during the year relative to timing of root growth. Most fine roots of spruce occur in the upper 15 cm of the soil (Kimmins and Hawkes 1978, Safford and Bell 1972); consequently, soil temperature at the 30-cm depth, for example, would not be directly relevant to seedling response. Johnson–Flanagan and Owens (1985) examined periodicity in root growth in relation to cell formation and cell elongation, and discussed problems with the concept of root growth capacity (RGC). It follows that microclimate influences on root growth may be quite different at different times of the growing season.

Temperatures of 4–5°C are thought to be the minimum necessary for root growth, although much higher temperatures of around 20°C are optimal for spruce root growth (Dobbs and McMinn 1977, Soderstrom 1981). However, Dobbs and McMinn (1977) found much greater height growth when soil temperatures were increased from 10 to 15°C than when they were increased from 15 to 20°C. This suggests that growth response to soil temperature is nonlinear and that increases of only a few degrees at the critical low end of the range may be important.

In the subboreal spruce zone soil temperatures are generally too low for optimum growth and development of seedlings. Consequently, site treatments are usually selected on the basis of potential for significantly increasing soil temperature. Cold root zone temperatures are known to inhibit root growth development following outplanting of conifers (Anderson et al. 1986, McMinn 1982, Nambiar et al. 1979). Anderson et al. (1986) suggest that cool soil temperatures can significantly affect root development and the subsequent ability of the seedling to withstand summer drought. But drought is unlikely to be a problem for most sites in the subboreal spruce zone. A more serious problem is reduced growth caused by impaired water and nutrient uptake by the root system (Heninger and White 1974, Lopushinsky and White 1984, Goldstein et al. 1985, Grossnickle and Blake 1985). Seedlings are unable to quickly establish an advantage over reinvading competing vegetation and become suppressed.

Burning will result in markedly increased soil temperatures, but the amount of increase depends on the depth of the remaining organic layer. Even a thin organic layer can be an efficient insulating layer, particularly if it is dry. During the summer on a spruce site in Finland, Viro (1974) measured average increases due to burning of 1.8°C through the 10–20-cm depths of the mineral soil and 3.2°C at the mineral soil and organic layer interface. Burning had reduced the humus and moss layers from 9 to 3 cm. Ballard et al. (1977) found no significant difference between burned and unburned sites for soil temperature at the 30-cm depth during a prolonged period of hot dry weather in August in south coastal British Columbia. The residual organic layer on the burned plot was described as somewhat thinner than the original forest floor. Endean and Johnston (1974) found moderate increases in soil temperatures following prescribed burns on well-drained and poorly drained sites on spruce-fir cutovers in Alberta. In July and August, following burning, temperatures were 3–4°C higher at the L–F interface, 2–5°C higher at the forest floor mineral soil interface, 2–3°C higher 2 cm into the mineral soil, and 1–2°C higher 46 cm into the mineral soil. The warming effect decreased over time, although by the 3rd yr following burning, higher temperatures of 1–2°C were still evident at the mineral soil surface and at the 2- and 46-cm depths.

By comparison, sites where mineral soil has been exposed, either by severe fire or by mechanical treatment, have much warmer soil temperatures than sites where residual organic surface cover exists. Dobbs and McMinn (1973) reported scalped sites were warmer than duff-covered sites by 6°C at the 5-cm depth and 2°C warmer at the 20-cm depth. Ballard et al. (1977) noted that the soil was 2°C warmer at the 30-cm depth under exposed mineral surface.

Air Temperature — Burning generally produces a greater diurnal range in the temperature of air within 1–2 m of the surface (Feller 1982). However, there are examples where no significant differences have been found (Ballard et al. 1977, Viro 1974). Inconsistencies between results that have been reported can usually be explained by differences in vegetation cover and species between sites, or changes in vegetation cover and species over time (Ahlgren 1981).

Light — The fundamental importance of light to the growth and development of seedlings has been well recognized (Stiell 1976, Dobbs 1972, Bassman 1984, Brix 1972). Reduced light levels from competing vegetation is the principal problem on NSR sites. It is generally agreed that the main objective for site treatment should be that competing vegetation must be removed and discouraged from reestablishing until such time as seedlings can maintain a competitive advantage (Eis 1981, McMinn 1982).

However, seedlings exposed to full sunlight may receive too much light, and some shading may help to optimize growth and development over the growing season. Damage to foliage from solarization (or chlorosis) may also be a problem (Ronco 1970).

Soil Moisture — One might expect higher evaporation from burned sites as a consequence of high surface temperatures and increased net radiation. However, transpiration has been eliminated through removal of covering vegetation. The residual organic layer acts as a very effective mulch and inhibits the movement of water from storage in the soil. Mulches are often used to conserve soil moisture (Davies 1975, Mullin 1965). Provided that burning has not been severe, stored soil moisture should tend to be conserved. Moisture conservation following burning has been reported (Viro 1974), but many observers have indicated that burned sites are much drier than mechanically treated sites (Dobbs 1972, Stiell 1976, Sims 1976, Rowe 1955). This apparent contradiction can be explained.

After vegetation is present, the picture is quite different. Vigorous new growth on warm soil demands water. The result is that sites that have been burned can have substantially lower soil moisture than untreated sites (Wright and Bailey 1982).

One should not be too hasty and conclude that burning usually results in unfavorable soil moisture conditions. Until recently, the majority of studies examining regeneration of lodgepole pine and white spruce have been concerned with seedbed conditions. Moisture conditions may be too dry for germination of seeds and the survival of young germinants; however, it does not necessarily follow that soil moisture would be too low for planted seedlings.

The impact of burning on soil moisture is influenced by rainfall regime. Seedlings planted on burned sites in dry regions are subject to drought. Rainfall often does not penetrate beyond the organic layer and so does not replenish lost soil moisture. In regions with a more equitable distribution of rainfall, however, drought is not a problem; and on wet sites a reduced soil moisture can be beneficial (Viro 1974).

HAZARDS

Frost — There appears to be a controversy regarding the extent to which burning makes a site susceptible to frost. Feller (1982) suggests that burned sites may have increased susceptibility to frost heaving. However, frost heaving is a mineral soil surface phenomenon that should be more prevalent on bare soil surfaces. The presence of an organic layer maintains the upper mineral soil horizons at warmer temperatures, thus making it less likely that fall frosts will lead to the formation of ice lenses which cause heaving (Heidmann 1976, Davies 1975).

It is also not obvious that seedlings planted on burned sites will be more prone to damaging spring frosts than seedlings planted on bare mineral soil sites. It is not cold surface temperature by itself that produces damaging frost but the coincidence of cold temperature with seedling vulnerability. Warmer soil temperatures in the spring will lead to earlier growth and development on bare soil sites. Unfortunately, if a region is subject to cold air outbreaks in the early part of the growing season, then it may be poor strategy to encourage early development.

Flooding — Excess moisture on subboreal spruce sites can be a problem. High water tables influence rooting patterns and periods of flooding produce physiological responses that have persistent effects on photosynthesis (Levan and Riha 1986). It is noteworthy that the pines are more tolerant to episodes of anoxic flooding conditions than are the spruces (Levan and Riha 1986, Minore 1970). Site treatment such as burning or mechanical mounding methods could reduce soil moisture and benefit seedlings planted on wet sites in the subboreal spruce zone. However, there may not be any long-term effects on soil moisture, and on very wet sites the effect of burning on soil moisture may be inconsequential.

Snow Pressure — Overwinter snow damage to young seedlings can be serious when competing herbaceous vegetation is present (Williams 1966). Fireweed (*Epilobium angustifolium* L.) is a herb that competes with newly planted seedlings and can be dense on some sites. The fireweed dies with frost in the autumn and falls over. A covering mat of dead fireweed may be formed and subsequent snow during the winter flattens the seedlings. After the snow has melted next spring, the seedlings may not be able to regain an upright growth habit with the result that growth and development are slowed and the seedlings may not survive. On sites where fireweed is not dense snow pressure is not a major problem (Eis 1981).

Pests — Fire has often been used as a means of purging the forest of pests, but some pests are encouraged by fire. There are a few pests such as Rhizina root rot (*Rhizina undulata* Fr.) and black army cutworm (*Actebia fennica* (Tausch.)) that are unique to sites that have been subjected to fire. The causes are not clear but are probably associated with changes in nutrients, microclimate, and competition.

Rhizina root rot is not a major problem in British Columbia, but where it exists on postburn plantations it can cause up to 80% mortality (Baranyay 1972). Where a burned site is known to be infested with Rhizina, planting should be delayed for 2 yr. There is little information available on microclimate influences. Laboratory experiments indicate optimum spore germination between 35 and 45°C, and optimum mycelial growth between 22 and 28°C (Baranyay 1972, Morgan and Driver 1972).

Black army cutworm has long been a pest of agricultural crops but it was not until 1964 that it was regarded as a forestry pest. The increasing number of plantations established in the 1st yr after burning has provided an opportunity for this pest with the result that populations have been increasing. The cutworm prefers feeding on herbaceous foliage but will readily defoliate conifer seedlings when herbaceous foliage becomes exhausted. Several years of warm dry weather are believed to be associated with outbreaks, and conversely, cool and wet years result in population collapse (Ross and Ilnytzky 1977).

Conclusions

Seedling growth and development in response to a variety of factors, including microclimate and treatments such as fire, have received intensive study for many years. There is a great deal of qualitative information available suggesting interrelationships. Tree psychologists are acutely aware that we do not have enough information about the basic processes affecting seedling growth and response to environment. There appears to be a modest amount of information published on photosynthetic processes of coniferous species and nothing on competing vegetation. We agree with Bassman (1984) that more detailed information on basic physiology is required, but we would also like to see some attention being directed towards understanding how the competing vegetation functions relative to seedlings.

On the other hand, we know much about micrometeorological processes and there are several promising models that can be applied (e.g., Bristow and Campbell 1986, Spittlehouse 1988). Such models must be calibrated to site-specific conditions, but before calibration can be carried out the micrometeorologist must know what the resolution of the predictions must be. Much more needs to be known about the sensitivity of seedling response to microclimate factors under natural conditions.

We believe there are opportunities for applying prescribed fire more effectively in rehabilitating NSR sites in the subboreal spruce zone in British Columbia. Useful guidelines can be developed for using fire and will require the incorporation of site-specific information gathered from integrated studies which examine fire impacts, microclimate, nutrients, and seedling response into fire effects models.

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Summary

SESSION II. CLIMATIC APPLICATIONS IN FOREST REGENERATION

The presentations at Forest Climate '86 showed that in terms of understanding and demonstrating the role of forest climate concepts in forest regeneration, significant progress has not been made in implementing current forest climate knowledge and technology. Climate, although one of the most important resources, is rarely considered in forest management decisions related to regeneration planning (e.g., development of rationales for site selection, planting strategies, and site preparation). Training forest managers to recognize and integrate climatic, soil, biological, and economic data and information when developing site prescriptions would improve their effectiveness.

Our poor success/failure ratio in regeneration activities clearly shows the inability to obtain a suitable return on our nursery and planting investments. To maximize this ratio with cost/benefit considerations, there is a need to identify short-term and long-term requirements of the future crop in terms of productivity. Climate is a primary factor in assessing or predicting the actual productivity and therefore can be used to identify variability in productivity as well as successes and failures.

The technology exists for integrating climate with physical and biological data into the analyses of regeneration successes and failures. However, this technology is not being used. Existing models are capable of identifying and partitioning the causative factors that directly influence productivity which, in turn, would allow foresters to move successfully from extensive to intensive forest management with minimum risk. At the macroscale, the effective integration of regional scale climate parameters (e.g., species-dependent heat units for defining species specific thresholds) could be used as a planning tool for the allocation of stock and the timing of site preparation planting activities. Mesoscale climate information could be used to define site-specific prescriptions which include the identification and modification of planting strategies in the field (e.g., spacing and site evaluation).

Therefore, it is recommended that:

1. methods for integrating climate information at the macro- and mesoscales into the preparation of silviculture prescriptions be developed and transferred as an operational planning tool for foresters;
2. climate information be integrated as a primary factor into forest site classification field manuals including the necessary information to interpret mesoscale climates from available data (e.g., macroscale climate and topographical data) to develop site-specific prescriptions; and
3. models that define the framework for silviculture prescriptions be developed and transferred to operational foresters. This will require biologically sensitive forestry data such as that provided by the growth layer reconstruction technology (e.g., TRIM system, Ontario Ministry of Natural Resources).

Discussion

A Perspective on Forest Renewal in British Columbia

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Abstract

British Columbia is Canada's most important timber-producing province. It is also Canada's most diverse province with respect to topography and climate. While this diversity can add to the quality of life for British Columbia, it can also present unique challenges to resource managers. This topographic and climatic diversity leads to a diversity in the province's forest profile. Add to this, the diversity and importance of other resource values such as wildlife and fisheries, the challenge to manage these complex ecosystems under the principles of multiple use is obvious. This complexity extends into the province's forest renewal initiatives and provides a major challenge to British Columbia's resource managers and users.

Résumé

La Colombie-Britannique est la principale province productrice de bois d'oeuvre au Canada. Elle présente aussi la plus grande diversité topographique et climatique parmi les provinces canadiennes. Bien que cette diversité puisse améliorer la qualité de vie des résidents, elle comporte aussi des défis uniques pour les gestionnaires de ressources. La diversité topographique et climatique a produit un profil forestier diversifié. Si l'on ajoute à cela la diversité et l'importance des autres ressources comme la faune et les pêches, le défi posé par la gestion de ces écosystèmes complexes dans un contexte d'utilisations multiples devient évident. Cette complexité s'étend aux initiatives de régénération forestière de la province et présente un défi majeur pour les gestionnaires et les utilisateurs des ressources de la Colombie-Britannique.

Introduction

In 1881, 105 yr ago, a British publication printed this article on British Columbia and the Canadian Pacific Railway Company:

"The New Yorkers are keen enough gamblers, and reckless enough at times, I admit, and yet it is impossible to believe that they are such fools as to put money into this mad project (the C.P.R.). I would as soon credit them with a willingness to subscribe hard cash in support of a scheme for the utilization of icebergs. The Canadian Pacific Railway will run, if it is ever finished, through a country frost-bound seven or eight months of the year, and will connect with the eastern part of the Dominion a province which embraces about as forbidding a country as any on the face of the earth. British Columbians believe prosperity will come to them when the line is made. This is a delusion on their part. British Columbia is a barren, cold, mountainous country — fifty railways would not galvanize it into prosperity."

I would suspect that there may be a few in British Columbia who, in spite of the passing of some 105 yr, might claim that British Columbia has still not been "galvanized into prosperity." While a few might claim this, I suspect that all would agree that significant portions of British Columbia are "forbidding," "barren," "cold," "mountainous," and, yes, even "frost-bound seven or eight months of the year."

In fact, British Columbia is the most diverse province in Canada. Even more, I submit that it is the **most diverse** of all the major forest regions of the world. Of course, the basis for this diversity lies in the province's climate and topography. The climatic variation spans from near-desert conditions in the province's southern Interior to the forbidding rain forests of the middle and upper coastal inlets and islands. Topographic variation ranges from the flatlands of the Peace River area to the gently rolling plateau of the north-central Interior to the ruggedness of the coastal mountain range and the Rocky Mountain themselves.

Obviously this interaction of climatic and topographic variation and diversity spawns a related diversity in the province's natural resources. For example, British Columbia has Canada's most important and diverse commercial forest resource, Canada's most important and diverse wildlife resource, and Canada's most important and diverse fisheries resource. Add to this the importance of the visual/aesthetic resource, an important ranching industry dependent on forest and range lands, the unparalleled treasure of its water resource, and unlimited diversity of forest recreation experiences, and the like, one can begin to appreciate the diversity of the forest resource and its uses.

While it is this diversity that affords a quality of life that makes British Columbia the best place in the world to live, it is this same diversity that brings with it immense resource management challenges — especially when it comes to planning the integrated use of the province's complex array of resources for the optimum benefit of all British Columbians.

These integrated resource challenges dwarf those of our major competitors such as the Scandinavian countries with their decisions on spruce, pine, and moose — or the southeastern United States with decisions on loblolly pine, slash pine, and deer. Since this complexity relates back to the province's diversity in climate, topography, and soils, I don't believe that it would be exaggerating too much to say that British Columbia would have a greater ecological diversity in one major drainage than would exist in an entire region or country of our market competitors.

With this extreme diversity of ecosystems and resources, the challenge in British Columbia was to establish a sound basis for site-specific decisions from forest harvesting to site preparation to regeneration, to integrated use. Thus, the decision was made to underpin the entire forest management program with an ecologically based foundation.

Since 1975, British Columbia has been systematically developing an ecosystem classification of the forests and range lands of the province. The classification system is based on the system developed in earlier years by Dr. V.J.

Krajina at the University of British Columbia. In effect, the system incorporates climate, soil, and vegetative data and the resulting classification provides a framework for forest and range management decisions as well as for scientific research.

This system is in operation throughout British Columbia although it is more developed and specific in the southern half of the province. Some examples of its use in British Columbia include:

1) **Land-Use Planning**

The assessment of land-use alternatives of a specific area involving its potential for uses such as agriculture, timber, wildlife, range, and the like.

2) **Seed Planning Zones**

The ecosystem diversity in British Columbia is such that a zoning process has been introduced that identifies seed planning zones with related restrictions on seed collection.

3) **Species Suitability**

The ecological classification system has become the major criteria in the province for selecting the most suitable species in considering natural and artificial regeneration options.

4) **Stand Tending**

The methodology and timing of cultural and stand-tending techniques including brushing/weeding, juvenile spacing, fertilization, and the like.

5) **Site Preparation**

The method and timing of site-preparation techniques including mechanical site preparation and prescribed fire.

6) **Harvesting**

The suitability of the area for harvesting and alternative harvesting techniques/equipment with respect to soil compaction and related site impacts.

7) **Nutrient Cycling**

The assessment of nutrient loss potential with respect to harvesting systems including whole tree skidding, forwarding, cable systems, etc.

8) **Wildlife Habitat**

The suitability of the area for wildlife habitat along with any related adjustments to harvesting/silviculture programs.

9) **Productivity**

The basis for assessing site productivity for forest inventories, growth projections, purchase/sale plans, etc.

Of course, climate is the principal ecosystem driving force. The diversity and variance in the forest ecosystem itself is primarily controlled by photoperiod, temperature, and precipitation.

Currently, 13 biogeoclimatic zones are recognized in British Columbia within which various subzones are also identified. At the zone and subzone levels, climate is the major controlling criterion in establishing these units. Below the subzone level, the more detailed classification levels incorporate soil types, slope/aspect, and minor vegetation.

Since I am not a forest ecologist, and before I get myself in real trouble amid a group of scientists, I'll make no further comment on the ecological classification in use in British Columbia and proceed to a description of forest management activities. In so doing, I'll include a personal perspective about how we are doing.

Reforestation

In 1956, 30 yr ago, only some 3 000 000 trees were planted in British Columbia. Almost all of these were planted on the lower coast with little more than research-type reforestation programs undertaken in the province's Interior. From that low level, the reforestation program continued to increase (even through the province's restraint period of the early 1980s) to where the final tally is expected to be some 155 000 000 trees planted in 1986. Targets have been announced whereby some 200 000 000 and 24 000 000 trees will be planted in 1987 and 1988, respectively.

The 240 000 000 planned for 1988 should provide a sound base for keeping regeneration (including natural regeneration options) balanced with the depletion but also make significant inroads into the backlog NSR sites. This is not to imply that increased attention should not be paid to regeneration prescriptions along with seedling and planting quality.

Brushing and Weeding

Although presently the reforestation program itself appears promising in British Columbia, I regret that the same cannot be said for much of the stand-tending programs. Unfortunately, the most productive sites in the province are the most brush-prone. Add to this the fact that these areas are the key interface with fisheries and wildlife values, restraints on some forest harvesting and silviculture activities are considerable. For example, the intensive mechanical site preparation of a brush-prone area on the coast would not be an option where the soil type is prone to erosion and the site is adjacent to an important salmon-bearing waterway. Unfortunately, alternative treatments involving prescribed fire and the use of registered herbicides are opposed by some vocal segments of society.

There is no easy answer to the current brushing and weeding dilemma and deficiency but it must be solved. The answer lies in a combination of factors including forest management techniques, research needs, public perceptions, political concerns, financial support, and, yes, professional will.

Juvenile Spacing (Pre-Commercial Thinning)

Overstocking is a problem in many young forests after logging. Where well-spaced regeneration of up to 2000 seedlings per hectare (depending on the species mix) is desirable, Mother Nature can regenerate these areas with tens of thousands and, not uncommon, over 100 000 trees per hectare. This excessive density is a more expensive challenge to the forest manager than if there was not natural regeneration at all on the site.

Juvenile spacing operations are required in these forests. Although a significant program was underway in British Columbia before the economic downturn in the early 1980s, it was reduced drastically during that trying period. However, I'm pleased to say that the juvenile spacing program in British Columbia is on the rise again.

Young lodgepole pine and hemlock forests are two of the major challenges in the fight against overstocking. In my opinion, the answer seems to lie in a combination of factors including the modification of site preparation methods and priorization directed toward the accessible sites and those with the most cost-effective potential to increase productivity.

Although I may be at odds with some of my colleagues, I think the answer to the older, excessively dense forests that cannot be spaced in any type of cost-effective manner is in utilization/marketing initiatives rather than rehabilitation.

Pest Management

Forty percent of British Columbia's forest land contains mature and overmature timber. Where the species are relatively short-lived, such as white spruce and lodgepole pine, Mother Nature's harvesting program is running rampant. For example, the mountain pine bark beetle has had a devastating effect on the forest lands of the western United States and Canada. In British Columbia alone, it has infested hundreds of thousands of hectares. Although not as widespread, the spruce bark beetle is also causing major damage to the province's white spruce stands. Even the new forests are not immune to pests — the spruce weevil damages young plantations. Squirrel damage to Interior lodgepole pine and porcupine damage to coastal western hemlock are other examples of pest damage to young forests.

Pest management and its research support have advanced considerably over the past 10 yr, but no one can say that this facet of forest management does not require more attention.

Forest Inventory

British Columbia has made major advancements in the use of computer technology and satellite-based information to further its forest inventory program. Unfortunately, these advancements are tempered by the fact that the basic inventory of the forest resource (viz. the second growth forests) requires a more comprehensive re-inventory.

Forest Research

In that forest research embraces silviculture, pests, products, logging, etc., the responsibility for various sectors is identified with different government/private/academic institutions. Some facets of British Columbia programs are second to none, while in others, some deficiencies are apparent. The value of forest research is still not adequately appreciated by management levels in British Columbia. During a CBC radio interview in Vancouver during 1986 National Forest Week, I was promoting the fact that forest research was an essential and integral arm of any forest management program and, without that arm, there was the danger of not realizing cost-effective forest management investments. The interviewer asked me: "O.K., you've convinced me on the value of forest research. But if it is so important and requires more attention, why haven't I heard senior management levels in the public and private forestry sectors ever mention the need for increased forest research initiatives?"

To be frank, I couldn't answer her question adequately. Again, I believe that many in senior management levels do not appreciate the importance of forest research — except as a "quick fix."

I would be remiss if I didn't spend a few minutes discussing British Columbia's forest land ownership pattern, its forest tenures, and its stumpage policy.

First, British Columbia is unique among the major forest regions in the western world in that 95% of its forest land remains in public ownership. This was a decision made over 100 yr ago and successive governments and four royal commissions of forestry have chosen not to challenge this historic decision. Thus, the challenge in British Columbia has always been to develop forest tenures that will transfer harvesting "privileges," and increasingly the forest management "privileges", to the private sector.

The tenure arrangements can be broadly divided into two types of management units. There is the area-based forest tenure which is primarily the Tree Farm License (formerly the Forest Management License) which has existed since the late 1940s — the direct result of the second Royal Commission on Forestry that took place in the mid-1940s. The second major management unit in the province is the Timber Supply Area which is volume-based. The Forest License is the main forest tenure in a Timber Supply Area. Thus, the main tenures for the forest industry in British Columbia are the Tree Farm License (area-based) and the Forest License (volume-based). In both tenures, the licensee is responsible for ensuring that the area harvested is regenerated with the desired species and at the desired density levels.

The stumpage formula used in the province has existed for almost 40 yr and provides for the reimbursement of forest management investments made on public land by the forest tenure licensees. The current reimbursement system which has been in use for several years is commonly called the "Section 88 reimbursement" which refers to the section of the forest legislation that provides for the reimbursement. Before this, the reimbursement was not a direct charge against the stumpage account but rather, a "forestry allowance" in the stumpage determination.

British Columbia has a complex stumpage policy and better men than I have faltered as they are given the task to try to explain the British Columbia stumpage system in 5 min or less. Thus, I'll leave the stumpage issue alone — except to say that any discussion on British Columbia's forest management programs and the public/private levels of responsibility must include some appreciation of the stumpage policy in existence.

Finally, I'd like to discuss the "British Columbia dilemma." I know that most Canadians look at everyone west of Calgary as being an eccentric lot. We always seem to be in some labor/management conflict or resource conflict.

At times, I ask myself why this is so. I especially did last spring when a mother telephoned me from Ontario to ask for material for her daughter's school project. Her young daughter had been asked to write an essay on why British Columbia's reforestation program was nonexistent while all other provinces had adequate programs. I resisted the immediate urge to say that the other provinces must all have better public relations offices and I talked to her about British Columbia's challenges and programs. By the end of our conversation, I got the impression that she was now rethinking her earlier assumptions and was beginning to see that the other provinces had a few problems too. But the impression that some Ontario teacher got from some newspaper report emanating from British Columbia is all part of the "conflict image" that I referred to — why is the resource issue always front-and-center and debated in the public arena in British Columbia? Well, I've rationalized this in the following two ways.

First, the obvious reason is the significant challenge to integrate resource use in the face of the unequaled climatic, topographic, and resource diversity of the province that I discussed earlier. Because the land base is unable to supply the **total** of the demands from all the special interest groups (i.e., timber, range, fisheries, wildlife, water, agriculture, conservationists, preservationists, etc.), any resource decision will unlikely satisfy all groups. Although this is a fact of life, it should not excuse the province's public/private resource managers from recognizing that this very diversity requires the highest quality and level of resource inventories, research, analysis, communication, and decision making.

In addition to the challenges concerning the complex diversity of British Columbia's forest resource, I believe there is another reason that spurs public debate on forest management in British Columbia. The new Forest Act of the late 1970s included a mandatory provision that the Ministry of Forests (now Ministry of Forests and Lands) must prepare a periodic report on the "state of the nation" regarding the province's forest and range resources. This provision was supported by all the political parties of the time. The report must be submitted to Cabinet and the legislation requires that it be made public at the following spring's sitting of the legislature. The first such report was prepared in 1979 and made public in 1980 while the second assessment was prepared in 1984 and made public in 1985. The intent of the report is not to be a propaganda publication telling people how great things are. Rather, the opposite is true. The report examines needs and programs and concentrates on deficiencies. So here we have the unique example of a government ministry's public report identifying deficiencies in programs. (In fact, I sometimes wonder whether with hindsight politicians would support such legislation today.) Only the Ministry of Forests and Lands has this obligation in British Columbia. No other province has a similar requirement for any of its government departments.

Thus, there is little doubt that such a report fuels the public debate on any inadequacies in forest management. More significantly, the report can even be used as a reference to document these inadequacies. I ask myself would I prefer:

1) a society where forest management program deficiencies are masked by a steady stream of "everything is great" propaganda where the public can bask in complacency thinking the days of superabundance will continue forever?

or

2) a society where forest management programs are the focus of public debate assisted by a periodic government publication that factually and honestly presents the facts on program deficiencies? This is a society that is certainly not complacent about the future, but one that realizes forest renewal is an essential component of the province's future well-being.

The choice for me is a simple one.

CLIMATE AND FOREST PRODUCTION

Session III. Climate Applications in Forest Growth and Development

Forest Production

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Discussion

Microclimate in the Establishment, Growth, and Development of Man-Made Forests

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Abstract

The man-made forest that we create after initial harvest will generally be established in a microclimate that may be considerably different from that which was present when the harvested trees were started. Good regeneration, survival and optimum growth in this man-made forest will depend on the selection of phenotypes genetically capable of favorable response under the physiological stress conditions imposed by that microclimate.

Research to achieve regeneration and optimum growth must be related to the organism that we wish to grow under the conditions that we expect it to grow. Simulation models relating plant–water relations and the photosynthetic response of an organism to the microclimate and soil water conditions of the site are one possible research tool. We should try to match species, rotation, and product to the anticipated recurrence probability of catastrophic events. Lastly, our harvesting practices should be designed to tailor site conditions to provide the best microclimate possible within the range of overall climate that we have to work with.

Résumé

La forêt que l'homme crée après la récolte initiale s'établira généralement dans un microclimat qui risque d'être fort différent de celui qui existait au moment du développement des arbres qu'on vient de récolter. La qualité de la régénération, la survie et la croissance optimale de cette forêt anthropique dépendent de la sélection de phénotypes génétiquement capables de réagir favorablement aux conditions de stress physiologique imposées par le microclimat.

La recherche sur la régénération et la croissance optimale doit tenir compte de l'organisme qu'on veut utiliser dans des conditions où on prévoit qu'il se développera. Les modèles de simulation établissant les rapports plante-eau et la réaction photosynthétique d'un organisme aux conditions microclimatiques et édaphiques du site constituent un outil possible de recherche. On doit tenter d'assortir les espèces, la rotation et les produits aux probabilités de manifestation périodique des désastres. Enfin, les méthodes de récolte doivent être adaptées aux conditions du terrain pour produire le meilleur microclimat possible dans les limites du régime climatique régional.

Introduction

Canada's natural forests are ours to use and perpetuate for future generations. As we harvest the trees from a forest, our desire should be to replace it with a man-made forest containing trees of equal or greater value for the next harvest. If a forest site is clear-cut, regeneration and subsequent growth will generally occur in a microclimate considerably different from that which was present during the establishment of the harvested stand, that is one with a greater light intensity, higher winds, higher surface and soil temperatures, and higher potential evaporation. Reforestation with the harvested species may be difficult; even more so with selected indigenous or exotic species to improve productivity. Successful reforestation and the acheivement of optimum growth will likely depend on matching of phenotype and microclimate, and should receive careful consideration before any harvest takes place.

General classifications of climate and vegetation are not sufficient to prescribe species and practices to reforest or to maximize the productivity of a forest site, although there is certainly a close association between climate and the natural occurrence of a particular type of forest. Most bioclimatic classifications rely on a close association between the heat and water economy of an area and the vegetation found there (Daubenmire 1956). The vegetation on a site is thought to integrate all environmental factors important to a plant (Daubenmire 1976). However, it is my contention that classifications based on the interaction of natural vegetation with local climate provide a poor basis for predicting the behavior of other species on that site or even the behavior of the same species on that site if the microclimate departs dramatically from that of initial establishment.

A TALE OF TWO TREES

To illustrate the importance of a proper species/microclimate match, I draw on the experience of early plantings of Monterey pine and coastal redwood in New Zealand. Monterey pine occurs along several off-shore islands and the coast of California from San Francisco southward in the Mediterranean climate type. Annual precipitation varies between 430 and 890 mm, and occurs mostly as rain during the winter. The months of July and August are frequently rainless but foggy. The species can survive temperatures to -8°C during the winter when it is dormant, and summer temperatures as high as 41°C (Scott 60).

The range of coastal redwood in California extends northward along the coast from Monterey, just south of San Francisco where its range overlaps with that of Monterey pine, to the Oregon–California border. Annual precipitation varies from 630 to 2000 mm and occurs mostly as winter rain. Minimum temperatures rarely fall below -10°C and maximums rarely exceed 38°C. The natural range of this tree is limited to areas with heavy summer fog (Fowells 1965).

During the 1850s and '60s, both Monterey pine and coastal redwood were planted on sites with climate similar to that of Monterey, California, throughout the North Island of New Zealand. By 1912, only 1% of the plantations of redwood had survived. By 1960, Monterey pine had become the major exotic planted in New Zealand; redwood was confined to shelterbelts, small plantations and specimen trees (Streets 1962).

The poorer survival of the redwoods in an environment and climate generally similar to that near Monterey has been attributed to insufficient summer fog in New Zealand. The frequent presence of dense summer fog along the coast of

California decreases water loss from the trees and may add to the soil water supply. It is apparently more important to the tree's survival than is the total amount of precipitation (Fowells 1965).

OPERATIONAL ENVIRONMENT OF AN ORGANISM

From the foregoing account, it should be evident to those who would use climatic data to describe growing conditions that such data must be related to the organism that one wishes to grow. The operational environment of a particular organism consists of the organism, all physical phenomena that enter into a significant relationship with the organism, and the relationships between the organism and these phenomena (Mason and Langenheim 1957). If climate and microclimate studies are to have a meaningful impact on increasing the productivity of forests, then the focus of such studies must be on the response of physiological parameters that effect tree growth to climatic parameters pertinent to growth. In the case of coastal redwood, it would have been necessary to determine the relationship between its physiological reactions to the presence of fog at all stages of the trees development; that is, how and when is the presence of fog operationally significant to the growth or survival of redwood?

Genetic Content of Natural Versus Man-Made Forests

SURVIVORS VERSUS GROWERS

It is impossible to discuss climate and tree growth without mentioning genetics. The trees that we see in a present day forest have been selected by natural climatic and biological forces over many generations. Daubenmire (1976) states that "Natural vegetation reflects the algebraic sum of all environmental factors important to a plant." I would modify Daubenmire's statement to read " . . . important to the survival of a plant." Naturally occurring forests can be considered as "living bodies . . . programmed by genes who have *survived*" (Dawkins 1978). As Staebler (1974) put it, "Nature's ruling criterion has only been the survival of its fittest forms." The evolutionary strategy of any species must be survival; any aspect of the phenotype's form that is useful to man is purely coincidental.

The differing strategies that trees use to survive are important to our understanding and management of them to optimize wood production. The strategy that we desire for the trees of a man-made forest must be one that maximizes growth within the constraints of the local climate.

To illustrate, the mechanism by which most of our trees survive the temperature extremes of the Canadian climate is dormancy. Dormancy may be induced by temperature, day length, or drought. In the Rocky Mountain region and in the much more favorable climate of New Zealand, lodgepole pine often ceases to photosynthesize in response to water stress, and can become physiologically quiescent even though temperatures are warm and day lengths are sufficiently long for growth. If the stress condition is maintained for a long time period, then true dormancy may occur, and even the reestablishment of favorable soil moisture conditions will not restore photosynthetic activity (Salisbury and Ross 1978). The Monterey pine that has been so successful in New Zealand never really becomes dormant there. It stops photosynthesizing under severe drought stress, but resumes root growth and photosynthesis within a day or so after rewatering (Rook et al. 1976).

Monterey pine thus exemplifies a type of response to precipitation that we should seek for optimum growth. However, if a tree does resume physiological activity, it faces the possibility of being unprepared (not hardened) when our harsh winter conditions demand that it be truly dormant to survive. As Bunting (1976) puts it, "To succeed in a climate where the season favorable to plant growth is limited by extremes of temperature, a provenance must either have an inbuilt timetable of appropriate length, or be able to endure the extremes." A good growing tree in the Rocky Mountain region would be responsive to summer precipitation and possess a timetable that prepares it for winter.

I think we should design forests in somewhat the same manner that hydrologists design dams, that is, to survive probable catastrophic events. Canadian forests are long-lived. They developed over several centuries and the trees have survived climatic events that occur with probabilities of 1:100 or even 1:1000. The trees we replace them with need only to be capable of surviving the events that are most likely to occur within their operational lifetime. If the forest we want will be operated on a 100-yr rotation, then the trees must be capable of surviving events that occur at somewhat longer intervals, perhaps the 500- or 1000-yr event. However, if we can operate a forest within a 20-yr rotation, then the trees may need only to survive the 100-yr event. To ensure the survival of the man-made forest, man would have to impose the "appropriate timetable" (Bunting 1976), that is, a rotation period within which disastrous climatic events would have a low probability of occurrence, and maintain seed and planting stock to replace both the trees harvested and those that didn't survive an untimely event that occurred within their rotation period.

Linkage Between Climate and Growth

There is no single climatic parameter that can be linked with growth to provide us with an easy way to prescribe the climate–growth links necessary to produce the man-made forest. Most growth and yield models have been derived from regression analyses (e.g., Ek and Monserud 1979, Fries 1974) of yield data which integrate all elements of the climatic and genetic composition that have shaped the stand. Models that integrate site and species characteristics may be advantageous for use in managing natural stands, where, for the most part, the site and species are considered constants (Curtis 1972), but such models are not advantageous to those of us who would like to change either site conditions or species.

NET PHOTOSYNTHESIS – THE ULTIMATE LINK BETWEEN CLIMATE AND GROWTH

Researchers are using photosynthetic variables increasingly to describe site productivity (Emmingham and Waring 1977, Reed 1980, Running 1984a). The bulk of tree growth is derived from the fixation of CO_2 during photosynthesis (Ledig 1976). Photosynthesis is a light-driven process of plants that combines CO_2 from the atmosphere with water taken up from the soil in the transpiration stream to make organic compounds. The uptake of CO_2 is controlled by the openness of the stomata through which the water of transpiration also escapes. Respiration is a temperature-driven process that converts some of the organic compounds created during photosynthesis into heat. Some of the heat energy of respiration is lost to the atmosphere; however, the more important part is trapped as energy in compounds that are used later in growth and differentiation (Salisbury and Ross 1978). Gross photosynthesis minus respiration equals net photosynthesis (PSN). Most models of photosynthesis require leaf temperature and leaf conductance in addition to the more commonly measured light intensity, air temperature, and atmospheric humidity (Helms 1976, Tenhunen et al. 1980).

MODELS – A WAY TO LINK MICROCLIMATE AND GROWTH

Emmingham and Waring (1977) postulated that the microclimate of forest sites that affects photosynthesis should show a close relationship with the productivity of those sites. Their model for net photosynthesis combined the effects of light, temperature, drought, and cold soils. They measured day length, average day and night temperature measured at 20 cm below and 1 m above ground, and total radiation as site-specific climatic parameters; leaf conductance and xylem water potential were the site-specific plant parameters linking microclimate to photosynthesis. This model was used as an index to seasonal and annual net carbon assimilation, and was successful in explaining productivity differences found on four forest microclimates.

Reed (1980) proposed a somewhat simpler model based on ecological, meteorological, and physiological variables. He derived a set of growth response functions that were in turn defined as indexes of air and soil temperature, solar radiation, soil water availability, and atmospheric moisture demand. Leaf biomass was used as the on-site indicator of photosynthetic productivity.

Running (1984a,b) developed a model to calculate the net photosynthesis of a tree species on a homogeneous site in response to microclimate variables. The plant water stress variables that influence photosynthesis were simulated with a daily transpiration model. The model was calibrated on real data from the Lubrecht Experimental Forest in Montana, and then used with climatic data from 42 different sites to estimate net photosynthesis on them.

There are some obvious advantages of process modeling approaches, such as Running's (1984a,b), over those using site-specific water stress measurements. The first is that we have a fair base of hydrological/climatological evapotranspiration models to draw from, which simulate plant water stress in response to climatic and soil variables (Federer 1979, Goldstein and Mankin 1972, Luxmore et al. 1981, Running 1984b, Running et al. 1975). The second advantage is that it may be possible to link the output from this type of physiological model with more traditional growth and yield models through modification of site indices to estimate the performance of other species and changes in site climatic conditions (Running 1981). Anyone who has tried to estimate the effect of soil moisture, which can be altered by various silviculture practices, on growth in models based on site indices knows how difficult this is (Swanson 1985).

The third and perhaps most important advantage of photosynthetic models such as Running's (1984a) is that they provide a framework that can be used to incorporate the results of various photosynthesis studies (e.g., Brix 1962 and 1967, Helms 1965, Schultz and Gatherum 1971, Sweet and Wareing 1968, Zavitkovski and Farrell 1968) to estimate integrated growth responses to microclimate parameters over several years. It is important that we be able to try various combinations of genotypes with the climate in question to see how they will perform under the range of conditions expected within a rotation. Such simulations will also provide new questions to which we can direct research to fill knowledge gaps that prevent us from applying physiological/climatological models to management problems.

TRANSPIRATION – THE LINK BETWEEN PLANT AND CLIMATOLOGIST

An understanding and physical description of the transpiration process, particularly the functioning of the stomata (Hall 1982, Running 1980, Schulze and Hall 1982), is fundamental to all of these attempts to link climatic or microclimatic variables and photosynthetic production. Transpiration is normally the major component of evapotranspiration (ET). The hydrological and climatological literature is replete with various models that describe ET solely from the atmospheric viewpoint in various environments (e.g., Monteith 1973, Morton 1975, Penman 1963). Most of the models originated by hydrologists or climatologists do not deal with the effect of plant water stress on stomatal conductance, although Monteith's (1973) does contain a stomatal resistance term that must be determined separately for use in the model. Monteith's model is often used as the transpiration submodel in those more physiologically based.

The transpiration models most useful in the study or prediction of microclimatic effects on photosynthesis are those that describe the water relations of a single tree. From a climatological standpoint there are disadvantages to single tree models, the most obvious being that water vapor transfer across a three-dimensional boundary layer surrounding a single leaf or tree is not describable with one-dimensional theory. However, at least two methods exist that provide direct measures or estimates of transpiration and do not depend on mass transfer theory — cuvettes and in-stem tracers.

Cuvettes, with controlled microclimates, can be placed on individual leaves, twigs, or branches to obtain direct measures of both transpiration and CO_2 exchange (Swanson et al. 1979). These data must be taken at locations that are representative of the whole tree crown and must be extrapolated to the whole plant. This is a serious but not insurmountable limitation on using the cuvette method with large trees.

The transpiration process in large trees can be studied with tracer techniques that measure the rate of sap flow (e.g., radioactive tracers: Kline et al. 1976; heat pulse: Lassoie et al. 1977, Swanson and Whitfield 1981, Swanson 1983). Of these, the heat pulse technique is the least destructive and most advanced theoretically (Swanson 1983) and it can be used to measure the rate of sap flow in branches or stems of coniferous trees (or hardwood trees with diffuse porous wood structure) with diameters greater than 4–5 cm. Sap flow data can be used as: (1) an independent measure of transpiration for comparison against data from cuvette and micrometeorological methods; (2) an indirect means of determining bulk vapor transfer coefficients in conjunction with micrometeorological methods; and (3) a means of extrapolating cuvette data to an entire tree.

WAYS IN WHICH MICROCLIMATE CAN BE CHANGED TO INFLUENCE GROWTH

Snow Accumulation and Loss — One effect of snow accumulation and/or loss on tree growth is on the amount of soil water on a site at the start of the growing season. The distribution and ultimate disposition of snow is profoundly affected by forest clear-cutting (Troendle and Leaf 1981). Up to 1.5 times more snow accumulates in clearings two tree heights across than under the uncut canopy (Golding and Swanson 1978) and gains in accumulation continue through time until the regrowth is at least 75% of the height of the surrounding canopy (Gary 1979).

Not all clear-cutting can be considered advantageous for growth. Gains in snow accumulation become progressively less as clear-cut size is increased, especially in windy climates where sublimation losses during long-distance transport and in situ evaporation can reduce accumulations to zero (Tabler and Schmidt 1973, Swanson and Bernier 1986). Snow loss also occurs along the south-facing edge of clearings greater than two tree heights across (N–S direction) due to the high energy input to the south-facing canopy from direct solar radiation and that reflected from the snow surface (Golding and Swanson 1986).

Running (1984a) simulated the effect of various soil moisture regimes on photosynthesis of lodgepole pine. He found that summer rains in the Rocky Mountain region were almost all lost as evaporation from interception on the canopy and were not effective in replenishing soil moisture and that almost all of the moisture for growth must be supplied from the snowpack. If Running's (1984a) simulations are indicative of what we could expect in Alberta, then the extra snow that accumulates in a two-tree wide clearing would allow a significantly longer spring growth period, and if the surrounding forest were not removed, this effect would continue for several decades until the new growth was almost as tall as the surrounding trees. Conversely, snow lost to evaporation during the winter would have an adverse effect on tree growth.

Wind — Wind has a direct effect on evaporation from snow and transpiration from leaves, with direct effect on soil moisture. The wind speed at the surface of small clearings 1–6 tree heights across is generally less than one-tenth the speed of that found above the canopy or in clear-cuts greater than 20 tree heights across (Swanson 1980). Evaporation from the snow in these small clearings averaged less than 50% that from a clearing 20 tree heights across. (The "red belting" that occurs in the portion of Alberta's foothills where chinook winds are prevalent is thought to be caused by evaporative water loss from the foliage, which cannot be replenished from the frozen soil [Henson 1952]. Damage is most severe on the windward side of trees, and those sheltered from the wind are undamaged [MacHattie 1963].)

Drainage — Drainage of peatlands directly modifies the near-surface microclimate by alteration of soil thermal and hydraulic properties. The surface soil temperature is generally increased, soil moisture decreased, and near-surface air temperature increased by draining water from peatland sites (Pessi 1958). Kaunisto and Päivänen (1985) indicate that water availability and soil temperature for tree growth are generally improved by drainage. Root growth (Tryon and Chapin 1983) and root resistance (Running and Reid 1980) are both influenced by temperature. While it is true that tree growth generally improves (Payandeh 1973), both the site and the trees on it may undergo an adjustment period before any improvement in growth will occur (Lieffers and Rothwell 1987). Models such as PROSPER (Goldstein and Mankin 1972) and DAYTRANS/PSN (Running 1984a, 1984b), which link plant functions to microclimatic parameters and soil water availability, should be useful for studying the time trend of the effects of various drainage strategies on tree growth.

Purposeful Modification of Microclimate

Staebler (1974) says we should dare to be different and innovative. Therefore, I would like to suggest some clear-cutting practices that would produce relatively permanent changes in microclimate and possibly improve tree growth. My experience is all with forests where snow is the dominant precipitation. However, some of these ideas might apply in areas where rain predominates as well.

Anderson (1966) suggested a wall and step type of forest manipulation, with cutting progressing from north to south. Such an arrangement would maximize shading to retard snowmelt. Anderson's purpose was to augment late season streamflow. However, the delayed snowmelt might also be advantageous for tree growth since the site would retain snow (possibly prolonging the period during which soil moisture is available) for about 2 wk longer than those less shaded. The increased snow accumulation and shading conditions could be maintained throughout the period of regeneration and juvenile growth by maintaining the leave strips for one-half the rotation duration.

It might be possible to establish a "nurse" forest to create and maintain a more moist and low evapotranspiration microclimate to increase growth. For instance, we have observed significantly faster growth of lodgepole pine in a 1 tree height wide, east–west oriented strip, than in either small circular openings less than 6 tree heights across or in 15-ha square clear-cut, approximately 20 tree heights across. One could create a series of 1 tree height wide clear-cut and uncut strips in a mature forest. The uncut strips might be managed on a 100-yr rotation for saw logs and the cut strips on a 20-yr rotation for pulp. Such a system would maintain the microclimate change in perpetuity to provide shade and the aerodynamic conditions for snow accumulation and retention in the intervening clear-cut strips.

Drainage is already a well-established practice in Finland (Päivänen 1984) and is becoming more prevalent in Canada. The recommended spacing for drainage ditches ranges from 25 to 50 m depending on the type of peatland site (Päivänen 1984). The creation of such a drainage network is a major alteration of the existing topography. It would therefore be interesting to look at the possibility of restructuring the landscape by deliberate orientation and spacing of the ditch network, during the implementation of the drainage network, to increase the solar radiation and wind regimes of the drained site in addition to the alteration of the soil water conditions.

Summary

Optimum growth in the man-made forest will not come about accidentally. We must be careful that we select species for their growth as well as their survival attributes. Research to achieve optimum growth must be related to the organism that we wish to grow under the conditions that we expect it to grow. Physical models relating plant-water relations and the photosynthetic response of an organism to the microclimate and soil water conditions of the site are one possible research tool. We should try to match species, rotation, and product to the anticipated recurrence probability of catastrophic events. Lastly, we should seek to tailor site conditions to provide the best microclimate conditions for growth that are possible within the range of overall climate that we have to work with.

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Growth and Development of a Natural Jack Pine Stand

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Abstract

Patterns of tree growth and development that occurred during the evolution of a 48-yr-old jack pine (*Pinus banksiana* Lamb.) stand in Northern Ontario are discussed. These patterns were reconstructed by employing growth layer analysis techniques. In the first three decades, annual fluctuations in growth parameters suggest a response to favorable and unfavorable climatic conditions. Mortality occurred in the third and fourth decades, peaking at the end of the third. In the fourth decade, growth was reduced and response minimal, possibly due to low vigor brought about by competitive stress and some defoliation. In relating climatic effects to tree growth the continual changes that occur within and between trees in a stand in their crown-stem-root relationships must be recognized.

Résumé

Le document examine les configurations de croissance et de développement des arbres survenues au cours de l'évolution d'un peuplement de pins gris (*Pinus banksiana* Lamb.) âgé de 48 ans dans le nord de l'Ontario. Ces configurations ont été reconstruites à l'aide de techniques d'analyse de la couche d'accroissement. Les fluctuations annuelles des paramètres de croissance, au cours des trois premières décennies, indiquent une réaction aux conditions climatiques favorables et défavorables. Au cours des troisième et quatrième décennies, on constate une mortalité qui atteint son maximum à la fin de la troisième. Pendant la quatrième décennie, la croissance est réduite et les réactions demeurent minimales, phénomènes qui sont peut-être le résultat de la faible vigueur des arbres attribuable au stress de compétition et à une certaine défoliation. Dans les rapports entre les effets climatiques et la croissance des arbres, il faut déterminer les changements continus dans les rapports cime-tige-racines des arbres d'un peuplement, et entre ces derniers.

Introduction

About 15 yr ago, extensive information on nutrient and biomass distribution was collected in a 30- to 35-yr-old stand of jack pine (*Pinus banksiana* Lamb.) as part of studies documenting nutrient cycling in a jack pine ecosystem (Hegyi 1972, Morrison 1973 and 1974, Foster and Morrison 1976). Data were also collected in younger and older stands.

The stand is currently being resampled as it approaches 50 yr to determine whether any unpredicted changes may have occurred, possibly due to the long-range transport of air pollutants. Details of the site, located on a stony coarse to medium sand of very low base saturation in Wells Township, about 75 km east of Sault Ste. Marie, Ontario, are given in the cited studies.

As part of the current studies, growth layer analyses were conducted using the TRIM (Tree Ring Increment Measurer) system to reconstruct the growth and development patterns of individual trees and of the stand (Fayle and MacIver 1986). Here we discuss briefly some of these patterns in relation to competition and climate.

The Data Base

Four polar plots of 16-m radius were randomly located in the stand, and all trees (live and standing dead) on the plots were numbered and mapped. Constraints imposed by associated studies prevented destructive sampling on a unit-area basis. Rather, increment cores were taken at stump height on the south side of every tree, and 21 jack pine were randomly selected to represent all but the largest (> 26 cm dbh) and smallest (< 8.1 cm dbh) of 3-cm diameter classes. Few jack pine occurred in the smallest class and one tree only was > 26 cm dbh. The selected trees were felled in the fall of 1985, cross sections taken at the base and 25-cm intervals up to 1-m height, at 50-cm intervals up to the apical 2 m, and from each internode within this 2 m. In the laboratory, ring widths were measured to 0.01 mm along the north and south radii of each section using the TRIM system. Standard tabular and graphical outputs include stem profiles and annual growth layer profiles for width and area; cumulative and annual height increment; specific volume increment, which is the annual volume of wood related to the surface area of the stem cambium that produced it (Duff and Nolan 1957); and cumulative, current annual, and mean annual increments in volume. Increment cores were also measured and data graphed.

For this paper, the 21 trees were grouped into three diameter classes: 8.1–14 cm, 14.1–20 cm, and 20.1–26 cm dbh. Average breast height diameters in 1985 were 11.5, 17.2, and 22.3 cm; for simplicity these are referred to as the small, medium, and large trees, respectively.

EFFECTIVE CROWN

The location within the crown portion of the annual growth layer where the cross-sectional area reached a maximum is considered to be the zone of maximum branch development and represents the cumulative growth contribution to the stem of branches in the active crown (Larson 1963). It occurs above the position of the lowermost live branches in the crown. This location, termed the effective crown base (Fayle and MacIver 1986), was identified on the growth layer profiles for area (see Fig. 2), and the effective crown length calculated as the difference between this height and total height.

CLIMATE

The closest appropriate climate stations to the jack pine stand (Lat. 46°25′N, Long. 83°23′W) are Sault Ste. Marie 2 (Lat. 46°32′N, Long. 84°20′W) and Turbine (Lat.

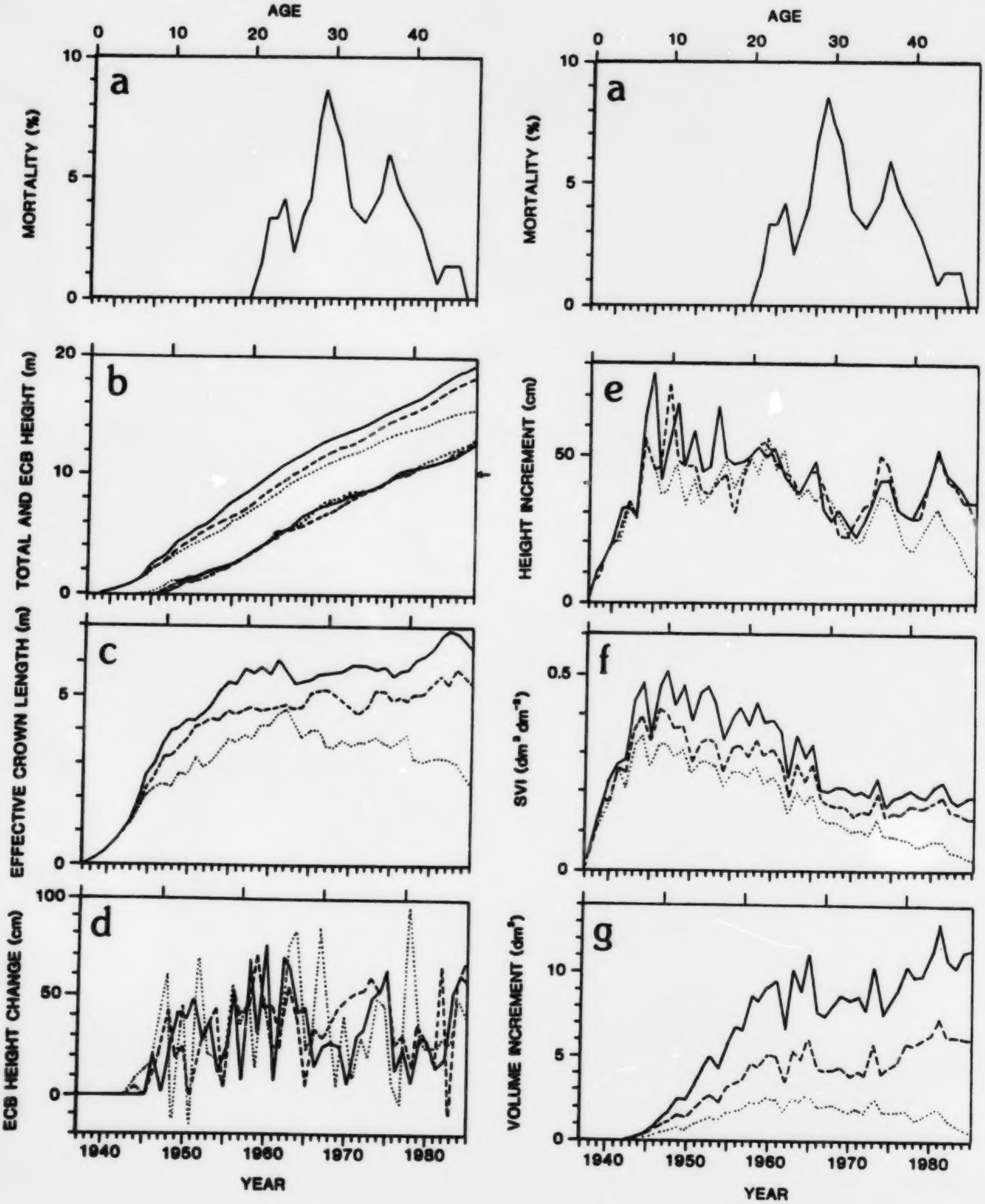

FIG. 1. (a) Annual mortality of all species as a percent of total mortality, based on a running 3-yr average; (b) cumulative height and height to the effective crown base (ECB) with arrow marking the base of the live crown in 1985; (c) effective crown length; (d) annual change in height of the effective crown base; (e) annual height increment; (f) specific volume increment (SVI); and (g) annual volume increment. Curves (b) to (g) are the averages for large (———), medium (----), and small (. . . .) trees (see text).

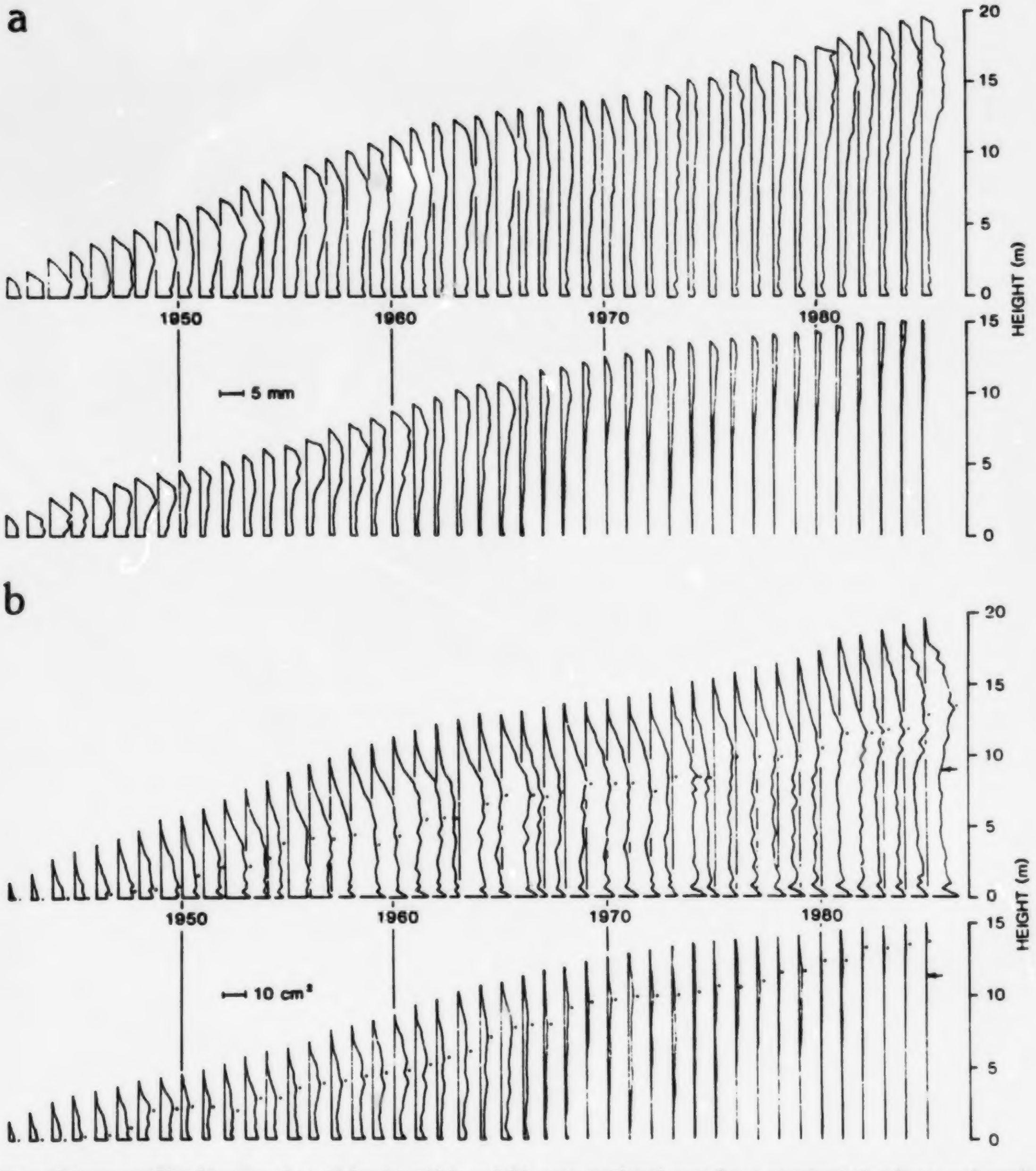

FIG. 2. Growth layer profiles from age 5 to 48 for (a) width and (b) cross-sectional area for a representative large and small tree (upper and lower curves, respectively, in each set). The dots indicate the base of the effective crown; the arrow, the base of the live crown in 1985.

46°23′N, Long. 81°34′W). Data, however, are not available for the first decade and a half of stand development.

Growth and Development

Trees that were present in 1985 as living and standing dead became established in 1936–62, with 45% of the jack pine being established by 1938 inclusive. This is taken as year 1. By the end of 1941 (age 5) 90% of all the jack pine were established. In 1985 the stand averaged 1500 trees ha^{-1}, of which 80% were jack pine, the remainder being small diameter white spruce, balsam fir, and red pine. Total basal area was 29 m^2 ha^{-1}. Based on the readable 60% of increment cores from the standing dead trees of all species, mortality occurred between 1958 and 1983 (age 21–46) and amounted to about 400 trees ha^{-1}.

Growth and development of the small, medium, and large trees in the stand are illustrated by the selected measures in Figure 1, with examples of growth layer profiles for

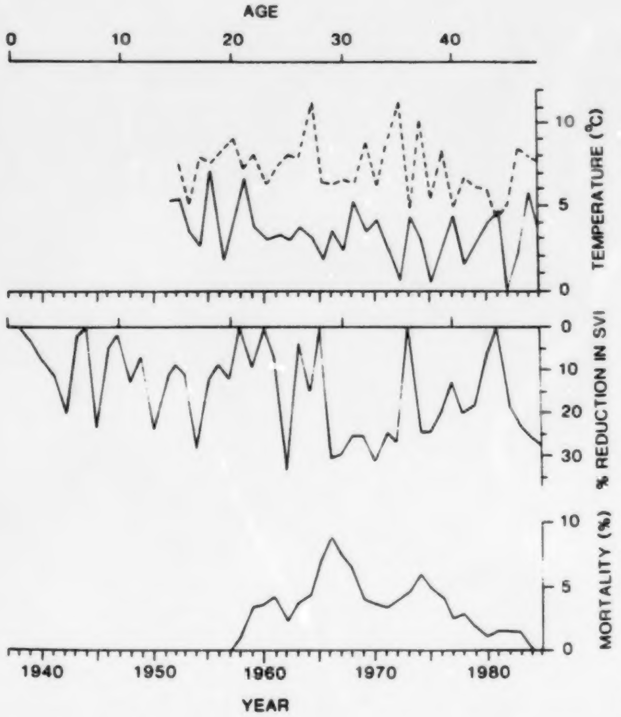

FIG. 3. Annual mortality of all species as a percent of total mortality (lower curve); the difference between actual specific volume increment and an estimated curve of "maximum" values expressed as a percent of the maximum, based on all trees (middle curve); and current April (———) and previous October (- - -) mean temperatures, adjusted for the relative distances between the Sault Ste. Marie and Turbine stations. Note that the October temperatures are moved over 1 yr, for example, October 1965 temperatures are plotted against 1966.

representative large and small trees given in Figure 2. Temperature data for April and the previous October are shown in Figure 3, related to deviations in specific volume increment.

Patterns are discussed first by decade of stand age and then in relation to climate.

FIRST DECADE, 1938–47

This decade is marked by a rapid increase in both annual height increment and specific volume increment, with little difference between the three sizes of tree in the first 7 yr. Subsequently, there is greater increase in height increment of the large trees and differentiation in effective crown lengths as the contribution to stem growth of foliage on the lower branches decreases with increasing shading. Concomitantly this leads to lessened production of wood on the lower stem of the small trees and specific volume increment falls behind that of the larger trees.

SECOND DECADE, 1948–57

Annual height increment of all three classes levels off but that of the large trees is consistently greater than the others, leading to increased differences in total tree height. However, no major differences occur in the height to the base of the effective crown and thus the effective crown length of the small trees is shorter, being 65% that of the large trees. Effective crown length still increases, but at a slower rate than in the first decade.

Specific volume increment declines in all classes as the proportion of stem below the crown increases; annual volume increment continues to increase. The annual fluctuations are the same for all tree sizes. By the end of the decade, current annual increment in volume of the small trees is not much more than a quarter that of large trees.

Maximum horizontal root extension is probably reached by the end of this decade (Shea 1973, Fayle 1975).

THIRD DECADE, 1958–67

As competition within the stand becomes severe mortality begins, with nearly half of the total mortality occurring in this decade, and reaching an annual peak around 1966 (age 29). Defoliation by insects may also be a contributory factor. Annual height increments show little differentiation between the three classes and progressively decline, indicating a degree of stagnation in the stand. At the same time the rate of upward movement of the effective crown base reaches a maximum, thus effective crown lengths no longer continue to increase and indeed are reduced toward the end of the decade in the large and particularly the small trees. Annual volume increment shows a major drop in 1955 (age 29), coinciding with the peak in mortality.

The marked reduction in width in the upper portion of the 1966 growth layers suggests that some defoliation may have occurred. The forest insect and disease survey report for that year noted pockets of severe defoliation in the Sault Ste. Marie District as a result of an influx of adult moths of the jack pine budworm (*Choristoneura pinus pinus* Free.) in July 1965. Similar reductions in the 1962 growth layers indicate that some defoliation may also have occurred earlier.

Studies by Morrison (1974) showed that vertical rooting depth on this site was 1.5 m at 30 yr. Below-ground growing space is probably limiting.

FOURTH DECADE, 1968–77

Mortality continues with a secondary peak around 1974 (age 37). As before, there is little difference between classes in the height to the effective crown base and the rate of its upward movement is somewhat lessened, probably in response to the improved growing space. At the same time there is an emerging differentiation again in annual height increment, thus the effective crown length increases slightly in the large trees and is more or less stable in the small trees.

In contrast to the previous decades, there is little annual variation in specific volume increment, other than a noticeable peak in 1973 (age 36), which coincides with a period of improved height increment. Annual volume increment also remained relatively stable during this decade following the drop in 1966 (age 29), but with a peak in 1973 and evidence of an increase in the two larger classes at the end of the period.

FIFTH DECADE, 1978–85(–87)

In the first few years of the decade, mortality tapers off. Effective crown lengths of the two larger classes continue to increase following the period of mortality, whereas that of the small trees declines rapidly due to the reduction in height increment and continued rise in the base of the effective crown. Concomitantly, specific volume increment is stabilized in the large trees and continues to decline in the small trees; likewise, annual volume increment increases in the large trees and decreases in the small trees.

There is an indication, however, in the last few years of data shown that decreases in effective crown length, annual height increment, and specific volume increment are occurring in the two larger classes and annual volume increment is leveling off. For the small trees, decline in all aspects is more rapid. Thus it would appear that a further period of reduced growth with death of the least vigorous trees is likely.

RELATIONSHIP TO CLIMATE

In 1962 and 1966, before and at the time of increased mortality, specific volume and annual volume increments are substantially reduced, the growth layer profiles showing particularly lessened thickening in the upper portions. Height increment also tends to be reduced in the following years. These reductions indicate a severe stress which may have triggered mortality; as noted earlier, this may result from defoliation by insects.

A visual comparison of the climatic and growth records provides no unequivocal, simple, and consistent relationship with temperature or precipitation, and it might be unrealistic to expect to find one. Regarding precipitation, for example, the 1976 growing season was the driest in the 24-yr record but there was no apparent influence on radial increment; temperatures were about average.

Attention was focused on the current April and previous October mean temperatures since these have been suggested as important for growth of jack pine in Ontario (MacIver 1987). The "blips" in specific volume and annual volume increments in 1973 and 1981 did occur when April mean temperatures were > 4.0°C, but in combination with two of the coldest previous Octobers (< 5.0°C) (Fig. 3). A lesser "blip" in 1977 also occurred with warm April and cold previous October mean temperatures. There was no response to the warm April of 1968.

Up to 1966 (age 29) the annual fluctuations in specific volume increment may reflect responses to favorable/unfavorable current climate, in combination with conditions in the previous year that would affect the growth potential. The general lack of response thereafter for several years may reflect a low level of vigor resulting from competitive stress, effects of defoliation, and an inability to respond to all but the most favorable conditions.

Conclusions

Growth of the jack pine in the stand is probably limited by soil characteristics and overall climatic conditions, aggravated too by some defoliation by insects. A vigorously growing stand would probably provide a better basis for examining climate-growth responses.

In the examination of climatic effects on tree growth, the continually changing crown-stem-root relationships within and between trees, and in the above- and below-ground growing space (see Day 1955), must be considered. Responses to climate can differ over time, depending on the vigor of the stand and its individual components. Growth layer analysis, particularly if used in combination with unit area sampling to take into account spatial relationships, provides a method of reconstructing and analyzing growth and development patterns.

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Climate, Water, and Drainage in Peatlands

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Abstract

Among biotic and abiotic factors influencing tree growth, climate is the most important. In northern latitudes summers are short and warm, winters are long and cold, and annual precipitation can exceed evapotranspiration. These conditions, coupled with generally flat terrain and impeded drainage, are conducive to peat accumulation. A hypothetical model showing how temperature and moisture help determine where peatlands can develop is presented. The effect that high water levels and low soil temperatures have on soil processes and subsequent tree growth is discussed. Tentative evidence of "watering-up" following forest harvesting is presented. Judiciously planned forest drainage systems are shown to quickly remove excess water and to improve the temperature climates of peat soils in northeastern Ontario.

Résumé

Parmi les facteurs biotiques et abiotiques qui ont un effet sur la croissance des arbres, le climat est le plus important. Aux latitudes nordiques, les étés sont courts et chauds, les hivers longs et froids, et les précipitations annuelles peuvent être supérieures aux valeurs d'évapotranspiration. Ces conditions, combinées à un terrain généralement plat et à un mauvais drainage, favorisent l'accumulation de la tourbe. On présente un modèle théorique qui montre comment la température et l'humidité peuvent déterminer les terrains favorables à la formation de tourbières. On étudie l'effet des niveaux des hautes-eaux et des basses températures du sol sur les processus pédologiques et la croissance des arbres. On présente des données provisoires «d'arrosage» après la récolte forestière, ainsi que des réseaux de drainage forestier planifiés judicieusement de façon à évacuer rapidement l'excès d'eau et d'améliorer les climats thermiques des sols tourbeux dans le nord-est de l'Ontario.

Introduction

Peatlands are a biophysiographic entity in the landscape characterized by excess moisture in the substrates, poor drainage, and impermeable subsoils (Gorham 1957). They are most common in cool areas where precipitation exceeds evapotranspiration (Boelter and Verry 1977). Under these conditions, climate can strongly influence the development of peat and peatlands. In this paper we discuss how climate influences where peatlands develop, the significance of water in peatlands, and how this helps to limit plant growth. We also briefly discuss how these limitations can be alleviated by peatland drainage. Research results presented are drawn from several studies conducted in northeastern Ontario peatlands over several years.

Role of Climate in Peat Formation

Several factors combine to determine where peat formation can take place. Gorham (1957) discusses the main factors influencing the development of peatlands — climate, geology, relief, and organisms. At the mesoscale, topography, soil texture, soil fertility, and fire frequency may be important. At the macroscale, however, climate becomes a predominant influence on the geographic distribution of peatlands. We therefore propose a hypothetical model of how two climatic variables, temperature and moisture, determine where peat can form.

Peat accumulates when the production of plant material exceeds organic matter decomposition. Both production and decomposition are governed by climate (Boelter and Verry 1977). The two processes, as depicted in our hypothetical model (Fig. 1), display different patterns regarding temperature. Primary productivity is low at low temperatures, but increases rapidly to a broad optimum as temperature increases (Lieth 1975). Decomposition, on the other hand, exhibits a steadily increasing curve. Peat accumulates when the difference between organic matter production and decomposition is positive. As moisture conditions change from moist to wet, the decomposition of organic matter is limited by increasingly anaerobic conditions, resulting in greater net organic matter accumulation. Peat formation is possible at higher temperatures only if conditions become wetter. Wet conditions result when combinations of temperature, soil texture, and landform conditions do not allow complete removal of precipitation by evapotranspiration and/or runoff (Gorham 1957).

The hypothetical model (Fig. 1) suggests several consequences. First, peatlands should be largely confined to a region that has a certain range of temperature conditions. Second, organic matter accumulation should be quite slow

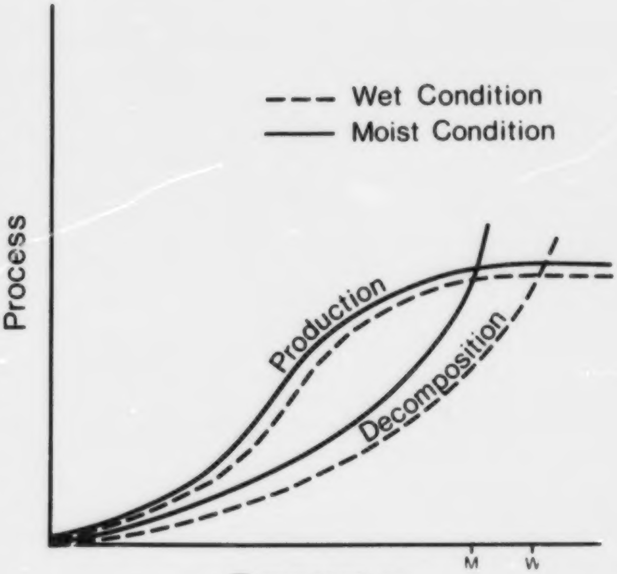

FIG. 1. Hypothetical model of peat accumulation.

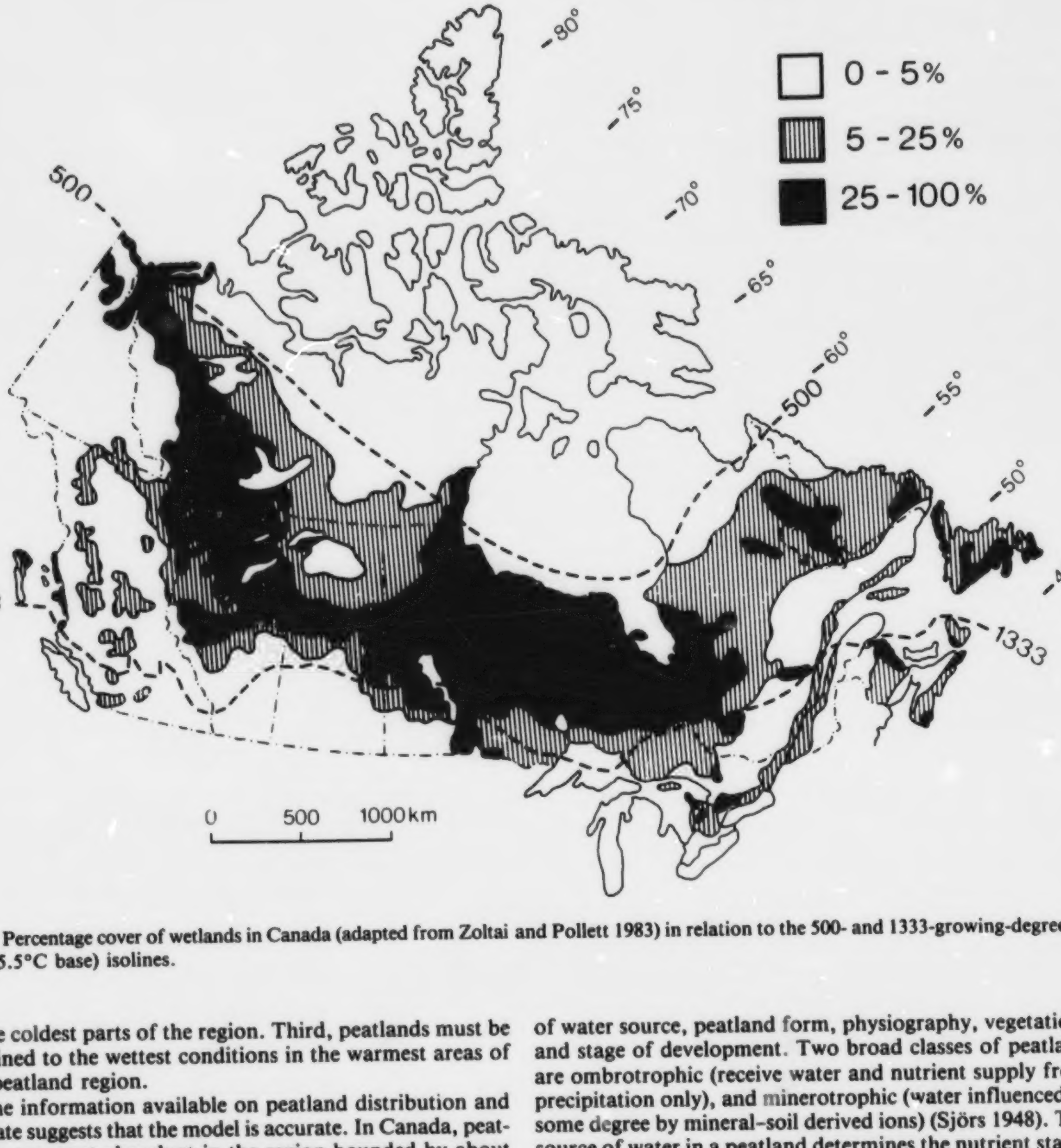

Fig 2. Percentage cover of wetlands in Canada (adapted from Zoltai and Pollett 1983) in relation to the 500- and 1333-growing-degree-day (5.5°C base) isolines.

in the coldest parts of the region. Third, peatlands must be confined to the wettest conditions in the warmest areas of the peatland region.

The information available on peatland distribution and climate suggests that the model is accurate. In Canada, peatlands are most abundant in the region bounded by about 500 mean annual growing degree-days in the north and 1300–1400 growing degree-days in the south (5.5°C base after Boughner 1964) (Fig. 2). Interestingly, this is similar to the range of the boreal forest and some of the southern arctic biotic zones (Ahti et al. 1968). According to Zoltai and Pollett (1983), peat depths are shallow throughout much of the Arctic, but increase toward the south, reaching a maximum in the Mid-Boreal and Low Boreal Wetland regions. In the latter region, peatlands become less abundant, and are mainly restricted to poorly drained, wet conditions.

Types of Peatland

Within the region where peatlands occur, many different peatland types can be found. These can be defined in terms of water source, peatland form, physiography, vegetation, and stage of development. Two broad classes of peatland are ombrotrophic (receive water and nutrient supply from precipitation only), and minerotrophic (water influenced to some degree by mineral–soil derived ions) (Sjörs 1948). The source of water in a peatland determines the nutrient status of the peat. Water supplied in the form of precipitation (rain and/or snow) is normally ion-poor and contributes to the nutrient deficiency of peatlands supplied solely from this source (Gorham 1957). Water that is mineral–soil influenced can vary from poor to rich minerotrophic, the latter characterized by circumneutral pH values and moderately high groundwater calcium contents. The kind of water entering a peatland determines in part the vegetation that will be present, but over time the vegetational development and associated peat accumulation can change the quality of the water that reaches the peatland (Boelter and Verry 1977).

In this paper we focus on forested peatlands in northeastern Ontario. These black spruce (*Picea mariana* (Mill.) B.S.P.) dominated forested swamps are of economic importance to many communities in the Boreal Forest

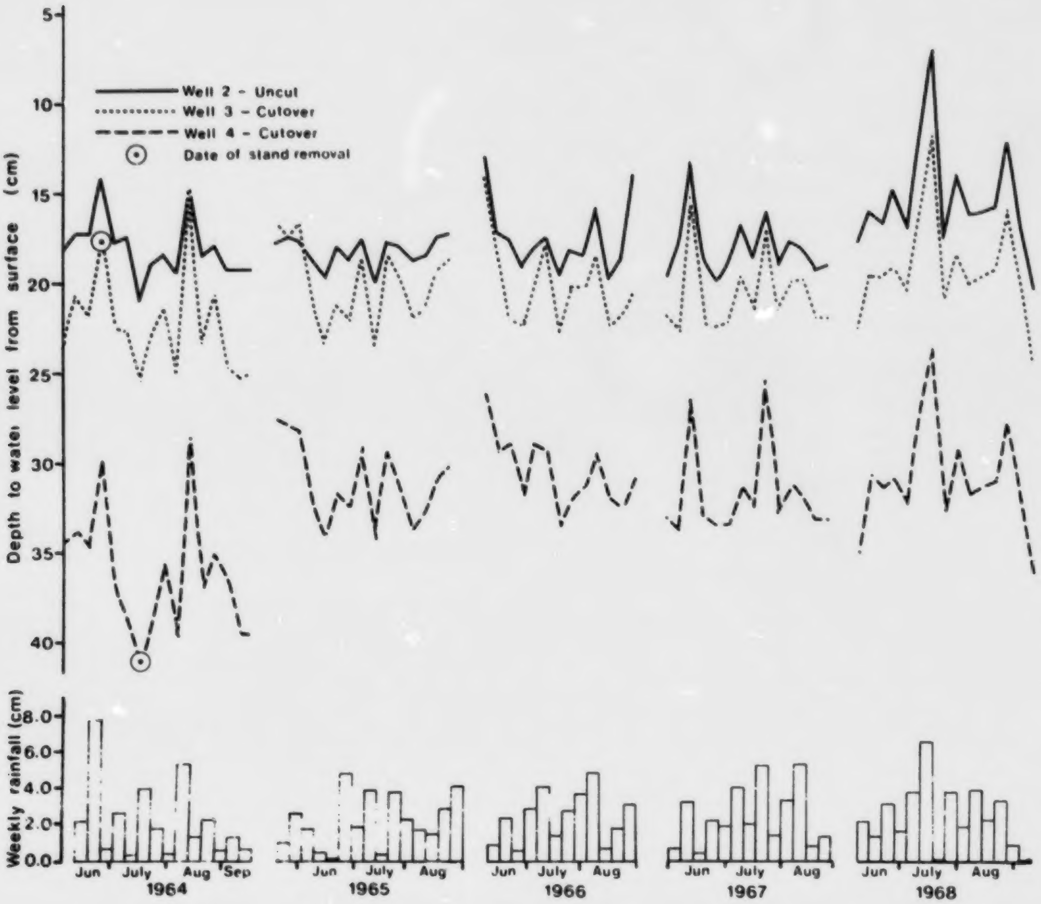

FIG. 3. Growing season hydrographs (1964–1968) for three wells near Cochrane, Ontario.

Region of Canada. The pulp and paper industry prefers to use black spruce because of its excellent pulping qualities. The productivity of this species on peatlands is generally low due to excess water in the substrate (Payandeh 1973).

Water Levels in Peatlands

High water levels are a feature of all peatlands. In forested swamps, the water level may be visible in small pools or channels for part of the year, but will never be very far below the soil surface. Water levels fluctuate during the course of the year depending on the amount of precipitation, its duration and intensity, the rate of runoff, the efficacy of evapotranspiration, and a host of physical characteristics of the substrate.

Amplitudes of water level fluctuation during the course of a year depend on the quantity and duration of precipitation, the degree of interception by the vegetation, evaporation, and transpiration (Bay 1967), flow into and out of the area by lateral, subsurface, or sheet surface flow, and the retention capacity of the peat soil (Leibfried and Berglund 1986). Rapid rises in water level following rainfall are due in part to the high moisture retention capacity (Boelter 1964) of peat soils.

Growing season and annual hydrographs have shown that a water level recharge occurs during the late fall following cessation of plant growth and/or in the spring following snowmelt (Heikurainen 1967, Reynolds et al. 1981). This is then followed by a steady decline to the end of the growing season, with fluctuations dependent on the amount of water entering the system from precipitation (e.g., Dai et al. 1974, Swanson and Hillman 1977). Depths to water level and the pattern of drawdown both depend on annual precipitation. The patterns remain somewhat similar for specific site types and can be very dissimilar for different peatland conditions (Heikurainen and Päivänen 1970, Dai et al. 1974).

Restrictions to Plant Growth Associated with High Water Levels

One of the most detrimental conditions to plant growth associated with high water levels is poor soil aeration (Gorham 1957). Low oxygen levels affect the growth of existing roots, the formation of new roots, and the viability of roots. Flooding or high water level can cause reduction in the rate of dry matter production (Kozlowski 1984). The decrease in root/shoot ratios due to flooding can predispose trees, especially seedlings, to drought injury when the water levels recede. Tree species vary in their tolerance of poor soil aeration (e.g., Zinkan et al. 1974), and suberized roots (woody and mature) may be more tolerant of low levels of oxygen than nonwoody juvenile roots (Coutts 1982). The general effect on growth, however, is negative and tree growth under conditions of low oxygen is often considerably below the capability of the species. Since root growth is restricted to the surface in poorly aerated soils, this might partly account for the surficial plate-like root systems so characteristic of black spruce.

The amplitudes and periodicity of water level fluctuations, as well as the velocity of horizontal water movement, can strongly influence the degree of oxygenation (Sparling 1966), the pH and the oxidation-reduction potential (Haavisto 1974), and associated chemical changes. Changes in the ion states of soil components can cause toxic levels of reduced forms.

Anaerobic soil conditions may also lead to the accumulation of undesirable soil gases, the end products of anaerobic decomposition (Ponnamperuma 1984). Finally, because wet soils tend to remain colder, growth and physiological activity, such as by tree roots and microbial decomposers, are reduced.

Water Levels in a Northern Ontario Peatland

To characterize water level changes and how these can affect productivity in forested peatlands, a series of water level wells were established during the late summer of 1963 throughout 110 ha of typical black spruce forest land in northeastern Ontario near Cochrane (Lat. 49°11′N, Long. 80°45′W). Elevations for each of these were established. The depths to water level were measured in each of the wells weekly during the growing seasons from 1964 and 1968. The amount of precipitation was also measured on a weekly basis. On part of the area, the forest was harvested during the summer of 1964.

Rainfall during the five consecutive growing seasons (Fig. 3) in the Cochrane area averaged 2.32 cm/wk (2.16–2.54 cm). Weekly distribution was variable throughout the study, and some high weekly rainfalls were recorded.

Only three wells are compared here. Wells 2 and 3, situated within 40 m of one another, occurred in the Alnus-herb poor type (OG 12, Jones et al. 1983). Well 4 was in the Alnus-herb rich type (OG 13, ibid.).

The water levels remained somewhat similar from year to year at Well 2, situated in the uncut stand (Fig. 3). Here, the water levels fluctuated between 13 and 22 cm below the surface, and maintained an average growing season depth of about 18 cm. A heavy rainfall in early July 1968 resulted in a high water level of 7 cm below the surface. The storage capacity of the substrate allowed for the uptake of the moisture. The drawdown during the following week was rapid.

Speculation has frequently been made, based on casual observation, that following clearcutting, water level rises on black spruce peatlands in Northern Ontario. A differential effect of harvesting on the water levels can be seen from the hydrographs for Wells 3 and 4 (Fig. 3). The black spruce stand around Well 3 was cut during late June 1964 and around Well 4 about 4 wk later. By observing the hydrographs and calculating periodic average depths to water level, it seems that following harvesting, general water levels and fluctuations associated with incoming precipitation were not different. A slight rise (2 cm) in the general water level was, however, noted the following year. The water levels in the uncut stands in the vicinity did not show this change. Since this somewhat higher water level was maintained over the next 4 yr at Well 3, we attribute the water level rise to harvesting.

At Well 4, the amplitudes of water level fluctuation during 1964 were considerable (between 27 and 41 cm below the surface), but again no significant reaction to harvesting was detected during the year of cutting. However, after the spring 1965 recharge of the system, water levels rose on average by 6–7 cm, attaining mean depths of about 32–33 cm. Average water levels again remained more or less at this depth for the ensuing 4 yr of the study, suggesting that removal of the stand was the cause. This is the first documented evidence for peatland forests in Ontario that water levels rise following harvesting.

Depths to water level, amplitudes of water level fluctuation, and general growing-season water level trends are generally similar for similar sites, and dissimilar for different sites even though situated near one another. Similar to the findings of Heikurainen and Päivänen (1970), we found that significant rises in water levels can occur in some site types, and insignificant in others.

Soil Temperatures in Peatlands

Peat soil tends to be cold. A study to monitor temperatures in typical peat soils was established under a stand of black spruce. A vertical stack consisting of 10 thermocouples (constantan/copper) was placed in a sphagnum moss hummock (*Sphagnum girgensohnii*) under a closed canopy of merchantable-sized black spruce. The uppermost sensor was positioned at the moss surface, the lowest at 30 cm below the surface. Temperatures were taken at 1-h intervals on specific dates during the 1965 growing season.

The temperature profiles depicted in Figure 4 clearly show that regardless of the date between June 10 and July 29, the peat layers near the surface were invariably warmer than those lower in the profile when measured at 1400 h, the warmest time of the day. Under the black spruce stand, the temperature at 30 cm on June 10 was barely above freezing; however, the temperature rose steadily to about 11°C by the end of July. On July 29, only a 3°C difference occurred from the surface to a depth of 30 cm. The temperature profiles shown here indicate that the growing season for roots may be rather short considering that near freezing temperatures were recorded just below the rooting zone in mid-June, and that temperatures in the upper part of the soil profile were already cooling by the end of July.

Peatland Drainage

Through forest land drainage, a technique that was developed in Scandinavia, effective water level modification has been accomplished. With drainage, the intent is primarily to quickly remove spring snowmelt and water resulting from heavy rain events and to prevent inflow of water from adjacent areas (Heikurainen 1960). Over a longer period, the goal is to lower water levels in the areas between systematically placed parallel ditches. This can be achieved by slow draining of water from the peat substrate, and by the action of evapotranspiration. To accomplish this, prescriptions defining drain spacing, depth of drains, and

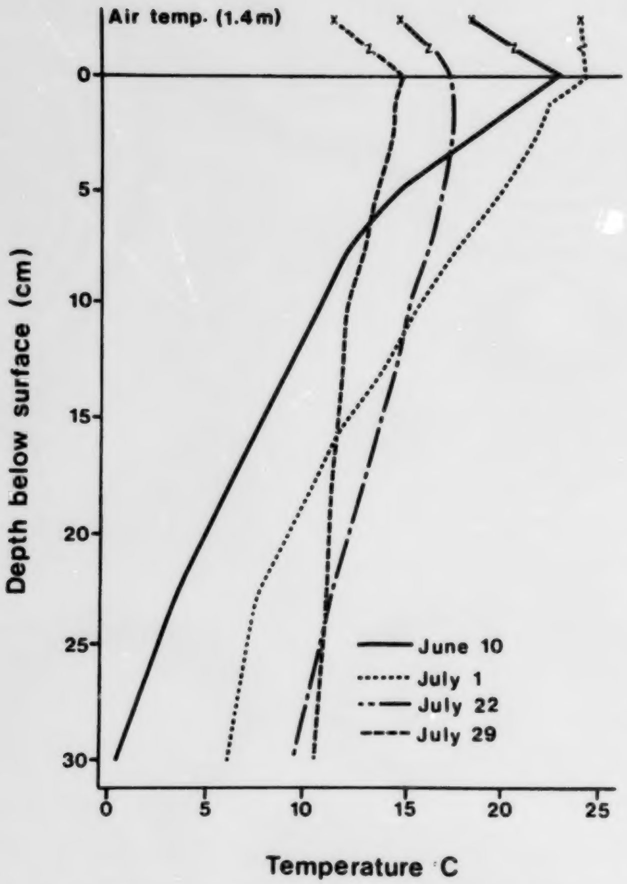

FIG. 4. Peat soil temperature profiles in a black spruce forest on 4 d.

simultaneous and subsequent silviculture activities for both predrainage and/or postdrainage have been developed. An example of the ditch spacing and depth prescriptions developed in Scandinavia is shown in Figure 5 (Braekke 1983). It shows that as the amount of summer rainfall increases, ditches must be closer together and/or deeper to achieve the desired water level depth of 30 cm. In practice, however, with very narrow spacing the ditch depths are also shallow.

The oldest documented peatland forest drainage in Northern Ontario was established in 1929 by Abitibi Power and Paper Company Limited (now Abitibi-Price Inc.) near Iroquois Falls (Payandeh 1973). The ditch system was not of the best design. In 1969 and 1970 studies were undertaken to evaluate how effectively the drains operated. Three Leupold-Stevens Type F water level recorders were installed at different distances from a ditch.

Figure 6 shows the reaction of the water levels at the three recorder sites following a heavy rainfall. Nearest the ditch, where the greatest amount of storage capacity occurred due to the greatest lowering of the water level, and where the bulk density of the peat had increased in the profile due to subsidence, the rise in water level was the greatest. Contrastingly, the water level recharge was smaller as distance from the ditch edge increased. This is due to the bulk density of the surface peats above the water level being materially less than that lower in the profile and having more voids to be filled with water. Nearer the ditch, the rate of drawdown naturally was also the greatest as water moves laterally more readily into the ditch and is carried out of the system. Water level at 10 m from the ditch was lower in the profile than that at 3 m (Fig. 6). This seeming anomaly was due to the increased subsidence that had occurred as one approached the ditch and the fact that all measurements were made from the present ground surface rather than from a common datum. At 33 m from the ditch edge, the recharge due to inflow from upslope and that from the heavy rainfall was low relative to the other two locations. Drawdown following the cessation of rainfall was also very slow. The water level profile at site 3 is therefore similar to that of an undrained control exhibiting minimal effect of drainage. It was concluded that nearer the ditches, water was effectively being removed from the site even after 40 yr of ditch operation.

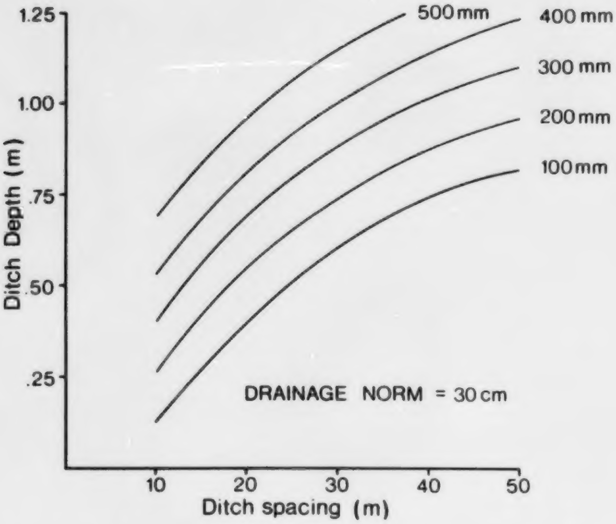

FIG. 5. Combinations of ditch spacing and depth required to achieve a drainage norm of 30 cm with summer precipitation ranging from 100 to 500 mm (based on Braekke 1983).

An example of the effect of drainage on the soil temperature of a clearcut black spruce swamp near Cochrane, Ontario, is given in Figure 7. During the 1986 growing season this effect was greatest in the upper 5–10 cm of soil early in the summer. Mean temperatures were about 3°C warmer at a 15-m drain spacing than at a 60-m spacing. Temperature differences among drain spacings in the upper layer diminished as the summer went on, but differences became significant at lower levels in June, and differences at 40 cm persisted through July. These temperatures appear to be related to water levels, which were at 53 cm at the 15-m spacing, 39 cm at the 30-m spacing, and 40 cm at the 60-m spacing during the summer of 1986.

The removal of excess water from the soil mitigates some of the problems associated with soil anaerobicity. The thermal regime is improved to increase both root growth and microbial activity. Subsequent increased decomposition and nutrient cycling ensure that both macro- and micronutrients become more readily available to plants.

Many peatlands tend to be nutrient poor. The increased growth rates of trees due to drainage will result in more rapid

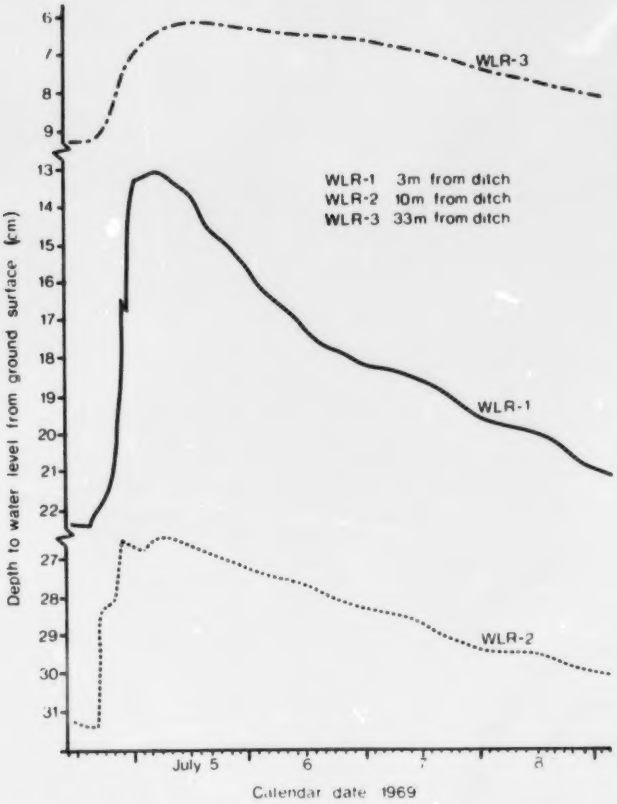

FIG. 6. Response of water level to heavy rainfall at different distances from a ditch in the Abitibi Drainage Area, northeastern Ontario.

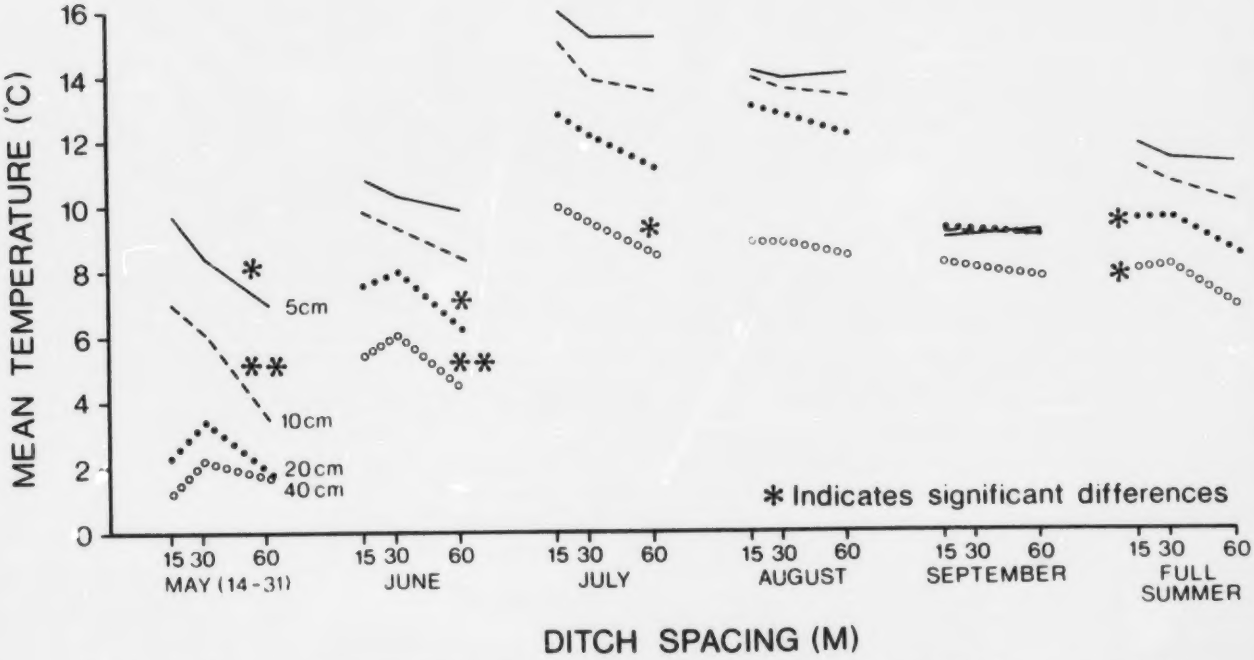

FIG. 7. Monthly mean soil temperatures at four depths across three drain spacings in a drained, cutover peatland.

consumption of nutrients. If a nutrient is already in low supply, for example, phosphorus and/or potassium, a nutrient deficiency may develop early. As such, the trees may increase growth only for a few years, then decrease dramatically as the nutrient supply becomes limiting. Hence, removal of excess water by drainage may not always result in sustained growth. To maintain improved tree growth it may be necessary to complement forest drainage with a program of fertilization on peatland sites.

Summary

Peatlands are complex ecosystems that occur within climatically determined limits. Many of the soil conditions found in peatland are climatically governed. These conditions include high water levels, poorly aerated soils, low soil temperatures, and frequently low levels of available nutrients, all of which limit tree growth. Forest land drainage can relieve many of these limiting conditions and thus allow tree growth to increase.

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Climate Considerations in Forest Fertilization and Stand Thinning

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Abstract

Climate affects the amount and availability of soil nutrients as well as the tree response to nutrients. Climate can therefore be expected to influence tree growth response to fertilization both directly and indirectly; however, few studies have established this relationship. Ways in which climate factors may influence tree response to fertilization and thinning are discussed with emphasis on moisture. Results are presented from our studies with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) of nitrogen–irrigation interaction in tree growth, effects of thinning and nitrogen fertilization on soil and tree water potential, and influence of June precipitation on height growth in relation to thinning and fertilization. A significant nitrogen–irrigation interaction in growth was demonstrated. Thinning increased soil and tree water potential but fertilization had no effect. Height growth in thinned stands was accordingly less affected by June precipitation than was growth in fertilized and untreated stands.

Résumé

Le climat a un effet sur la quantité et la disponibilité des éléments nutritifs du sol ainsi que sur la réaction des arbres aux éléments nutritifs. Ainsi, le climat pourrait modifier, directement et indirectement, la réaction de croissance des arbres à la fertilisation. Cependant, rares sont les études qui ont réussi à établir cette relation. On examine, avec une insistance particulière sur le facteur d'humidité, les modes d'influence des facteurs climatiques sur la réaction des arbres à la fertilisation et à l'éclaircie. Les résultats présentés proviennent de nos études, chez le douglas taxifolié (*Pseudotsuga menziesii* (Mirb.) Franco), de l'interaction azote-irrigation dans la croissance de l'arbre, des effets de l'éclaircie et de la fertilisation par l'azote sur les ressources en eau potentielles du sol et de l'arbre, ainsi que de l'effet des précipitations tombées en juin sur la croissance en hauteur relativement à l'éclaircie et à la fertilisation. On a démontré une importante interaction azote-irrigation dans la croissance. L'éclaircie a accru les ressources en eau potentielles du sol et des arbres, mais la fertilisation n'a eu aucun effet. Les précipitations de juin n'ont donc pas eu autant d'effet sur la croissance en hauteur des arbres dans les peuplements éclaircis que sur celle des arbres dans les peuplements fertilisés et non traités.

Introduction

Intensive forest stand management is presently carried out only on a small scale in Canada but indications are that considerable investment in fertilization and thinning will be made in the future to meet increasing demands for wood products. Prediction of response to these treatments under different site and stand conditions will therefore be important to maximize returns. Climatic influences on responses are likely very important but very little research has been done on this subject. Some aspects of these influences and related research with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at the Pacific Forestry Centre are presented here.

Several forest fertilization research projects have covered wide geographic ranges in which considerable climatic variations can be expected. One of these projects is the Interprovincial Forest Fertilization Program in which field trials with several boreal forest conifers have been established in seven provinces across Canada from Alberta to Nova Scotia (Weetman and Krause 1979). Another is the Regional Forest Nutrition Research Project in which installations with Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) have been made on a wide range of sites in western Washington and Oregon (Peterson et al. 1984). A project in Sweden with Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) has covered latitudes from 56°N to 66°N (Möller 1983). Nitrogen has been used in all projects but some trials have also included phosphorus and potassium. None of the projects has related growth response directly to climatic variables but it is noteworthy that a response has been obtained under a broad range of climatic conditions. The Swedish project related the response to latitude and altitude and thereby possibly to climate with an increasing response from 56°N to 60°N and no further significant change farther north to 66°. Response was best at an altitude of 200–300 m.

Instead of studying treatment effects in different climatic regions, another approach to investigate climatic influences is to relate response variation from year to year for any one site to changes in climatic variables for that site. A study of this kind was done at the Canadian Forestry Service's Shawnigan Lake installation as described later. An alternative approach is to regulate the microclimate by a treatment such as irrigation.

Although the influence of climate on growth response to fertilization has received little attention, there is good evidence to show that some conditions and processes leading to this response are strongly affected by climate. There are many ways in which climate can influence responses. Some are associated with the natural soil fertility in terms of nutrient content and availability, others to the fate of fertilizer applied and availability to trees. Also, climate may affect how trees react to increased nutrient uptake; in fact, even damaging results may occur. Examples of these influences are now given but no extensive review is intended.

Climate, Tree Nutrition, and Thinning Effects

The cycling of nutrients in the ecosystem, including gains and losses, plays a very important role in tree nutrition and growth, and will influence the growth response of trees to fertilizer application. Climate affects this cycling in many ways. Inputs can occur from precipitation, dust, mineral weathering, and biological fixation; losses through leaching, volatilization, and runoff; recycling through litterfall and organic matter decomposition. Rainfall and temperature have major effects on these events (e.g., Jurgenson et al. 1977, Krause et al. 1978, Cole 1981, Johnson et al. 1982, Parker 1983, Gosz 1984). The low productivity of boreal forest ecosystems is related to a slow nutrient cycling and accumulation of nutrients in organic matter in the forest floor (Krause et al. 1978). Low mean annual soil temperature and unfavorable substrate composition are reasons for the low rate of biological activities involved in organic matter decomposition. In some locations moisture conditions can be important. Nitrogen fertilization can therefore improve productivity on a temporary basis but could also have longer term effects by changing forest floor development (Krause et al. 1978). Stand thinning could improve soil temperature and thereby increase organic matter decomposition and tree growth (Piene 1976). Thinning can affect moisture conditions with consequent beneficial or harmful effects depending on moisture status. Moisture could be important indirectly by its influence on soil temperature (Heal 1978). Bunnell et al. (1977) presented a model of the influence of moisture and temperature on microbial respiration, and demonstrated a good prediction of climate effects on decomposition of a range of little types.

Input of nutrients from precipitation varies greatly with sites depending on distance from source of production, atmospheric conditions, and the amount of precipitation. Reported values for nitrogen for International Biological Program sites range from 1.1 $kg \cdot ha^{-1} \cdot yr^{-1}$ on a spruce site in the Soviet Union to 22.8 $kg \cdot ha^{-1} \cdot yr^{-1}$ at Solling in West Germany (Cole 1981). The latter value is about one-third of the nitrogen required for optimal growth.

Nitrogen fertilization with urea can result in losses by ammonia volatilization under certain climatic conditions. Losses can be considerable when application is followed by dry and warm weather (Crane 1972). Urea, or ammonium, the product of hydrolyzation, must be quickly moved down in the soil by rainfall to minimize losses. Based on records of rainfall and consideration of soil temperature, Heilman et al. (1979) proposed guidelines for season of urea application for various regions in the Pacific Northwest having wide variations in soil and climate. Similar concerns about climatic and seasonal effects on nutrient losses, availability, and uptake following fertilization and the resulting growth response have been raised in Sweden. Studies have shown that urea and ammonium nitrate produce different growth responses depending on season of application (Hagner 1973). Urea could be applied on a snow cover but a poor response was obtained with application during the thaw period in spring. Ammonium nitrate, however, should only be applied on bare ground and the best result was obtained with a late summer fertilization. The effect of applying nitrogen fertilizers (urea and ammonium nitrate) on snow, regarding nitrogen losses, uptake, and growth of lodgepole pine (*Pinus contorta* Dougl.) and Douglas-fir is being studied with the use of 15-N application at the Pacific Forestry Centre (V.G. Marshall, pers. comm.).

Fertilization may result in damage to trees under certain climatic conditions. In a study with Douglas-fir, Miller and Pienaar (1973) found increased snow and winter breakage as a result of stimulation of foliar growth following nitrogen fertilization. They also quoted similar reports for Scots pine and Norway spruce. Damage described as "winter drought" was observed in Norway spruce and attributed to nitrogen fertilization (Tamm 1974). Stand thinning provides both an opportunity to stabilize stands against wind throw as well as a hazard from this source. Several factors such as timing, frequency, and intensity of thinning and interactions with soil and tree species will affect stand stability (Persson 1969). Snow breakage can also be a problem of particular concern immediately after the first thinning (Shepherd 1976).

Soil water deficits severely limit forest growth in many forest regions and knowledge of water–nutrient interactions is therefore important in formulating guidelines for forest fertilization. Possible sources of water–nitrogen interaction in tree growth were reviewed by Brix (1979). Our research at the Pacific Forestry Centre has dealt with some of these aspects in relation to nitrogen fertilization and thinning of Douglas-fir and results are presented briefly in the following section.

Water, Nutrients, and Tree Growth: Studies at the Pacific Forestry Centre

WATER-NITROGEN INTERACTION IN GROWTH

Water–nitrogen interaction in growth was studied in a 23-yr-old Douglas-fir stand near Victoria, British Columbia. Single-tree plots with trees of the same diameter at breast height (dbh) were subjected to four treatments: (1) fertilized at a rate of 448 kg N/ha using ammonium nitrate, (2) irrigated in the summer of the 1st and 2nd yr with 25 mm of water per week, (3) given the combined fertilization and irrigation treatments, and (4) left untreated (Brix 1972). In the 1st yr, dbh was increased by 16, 15, and 59%, respectively, by these treatments above growth of untreated trees; similar effects were obtained in the 2nd yr. To explain this treatment interaction rate of photosynthesis, leaf growth and leaf mineral concentrations for trees with these treatments were examined. No treatment interaction was apparent in leaf growth. Water stress reduced the rate of photosynthesis similarly for branches from fertilized and control trees but initial maximum rates were different. Data on mineral nutrient concentrations (N, P, K) of foliage showed no effect of irrigation alone but increased concentrations of N and P when irrigation was combined with N fertilization, thus providing a possible interaction in growth. The growth interaction found indicates that nitrogen fertilization will be most effective on sites and in years with favorable soil water conditions. Similar conclusions were made about height growth in another experiment described later. No interaction in Douglas-fir growth, only an additive effect, was found by Strand (1964) in a study in Oregon. Also, an even better response to nitrogen fertilization than that shown here was demonstrated in the Shawnigan Lake experiments (Barclay and Brix 1985) where summer drought is severe but where nitrogen deficiency is also greater. A water–nitrogen interaction may well depend on the degree of deficiency of water and nitrogen and possibly also on other growth limiting factors, for example, other nutrient elements (Brix 1972).

NITROGEN FERTILIZATION AND THINNING EFFECTS ON TREE AND SOIL WATER STATUS

As indicated, the growth response to nitrogen fertilization may depend on the soil water conditions. In addition to the possible nitrogen–water interactions listed above, it is conceivable that nitrogen fertilization by promoting foliage production could increase the water use in forest

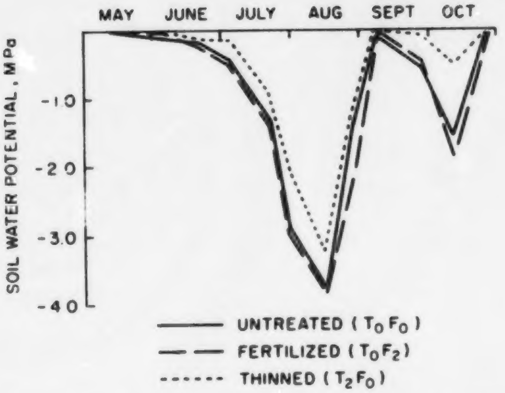

FIG. 1. Effect of nitrogen fertilization and stand thinning in a Douglas-fir stand on soil water potential during the growing season 9 yr after treatment.

stands; possibly to the extent where this could be critical for tree growth.

Our field project at Shawnigan Lake, British Columbia, in a 24-yr-old Douglas-fir stand investigates the biological basis of growth responses to nitrogen fertilization and stand thinning (Crown and Brett 1975). The basic treatments include three levels of fertilization (0, 224, and 448 kg N/ha as urea) and three levels of thinning (0, 1/3, and 2/3 of basal area removed) for nine treatment combinations. Two replicate plots were established in 1971 and two in 1972 for each treatment. One study in this project deals with treatment effects on soil water use and the resulting soil and tree water stress during the growing season and over the years since treatment.

The soil water potential was measured with soil psychrometers placed at different soil depths in the rooting zone (10, 20, and 40 cm) and at different distances between trees (Brix and Mitchell 1986). The water stress of branches was measured with a pressure bomb (Waring and Cleary 1967). Changes in foliar area and biomass following treatments were measured as described by Brix (1981).

Fertilization increased the leaf area by as much as 50% after 7 yr and thereafter in unthinned stands from a leaf area index of 5.9–8.8 (Brix 1981). However, this had little effect on soil and tree water potential during the 10-yr study period (Brix and Mitchell 1986). Figure 1 shows that fertilization had no effect on soil water potential throughout the ninth growing season after treatment although the leaf area was increased by 50%. Increased tree growth (48% in volume over 9 yr, Barclay and Brix 1985) was therefore accomplished with little or no further water use. The most likely explanation is that nitrogen fertilization improved stomatal control of water losses and this is presently under investigation.

Thinning, by reducing canopy density, greatly increased soil water potential by as much as 1 MPa during the dry summer period (July–September) (Fig. 1). For all 10 yr under study an increase in soil water potential, that is, decrease in water stress, averaged 0.3 MPa both with and without fertilization. Pre-dawn tree water potential was increased similarly but decreased during the morning to control level presumably because of exposed crowns (Brix and Mitchell 1986).

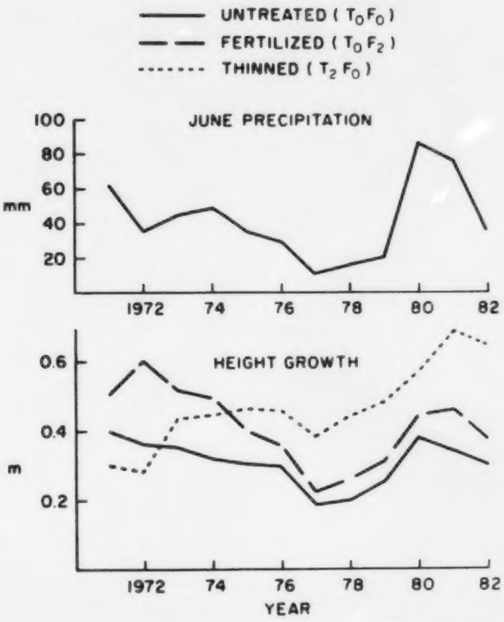

FIG. 2. Height growth of Douglas-fir in plots that were either untreated, nitrogen fertilized, or thinned for the 12 yr after treatments and June precipitation in those years.

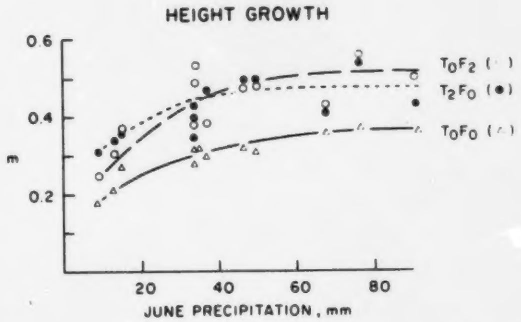

FIG. 3. Relationship of height growth to June precipitation for Douglas-fir trees in plots that were either untreated, nitrogen fertilized, or thinned.

The thinning and fertilization effects on soil water potential shown here relate to the growth relationship presented in the following section.

RELATIONSHIP OF HEIGHT GROWTH TO PRECIPITATION

In the Shawnigan Lake trials, height and diameter growth has been recorded on a yearly basis for some sample trees and every 3 yr for all trees since treatments. Daily records of precipitation, solar radiation, air temperature, and humidity are obtained from the weather station which is part of the British Columbia Ministry of Environment climate station network (Shawnigan CFS).

The height growth in years since establishment of the 1971 plots is given in Figure 2 for trees from plots which were (a) untreated (T_0F_0), (b) thinned without fertilization (T_2F_0), and (c) fertilized without thinning (T_0F_2). Height growth on this site is usually confined to the month of June.

The best relationship of weather parameters to height growth was obtained with June precipitation. In addition to being the month for height growth it is also in June when critical soil water deficits begin as illustrated for year 9 (1979) in Figure 1. The pattern of height growth shown in Figure 2 results from climatic effects as well as changes in response to treatments with time as a result of factors such as depletion of nutrients added in fertilization and stand development following thinning. An attempt to eliminate time changes with treatments was made in a multiple regression analysis with subsequent evaluation for year 5. The data arrived at in this way are shown in Figure 3. An r^2 of 0.88 was obtained when all data were considered as a single group. A June precipitation of 40 mm, which is the average for the 12 yr, appears to be the critical level for height growth on this site; drastic reductions occur below and little change occurs above this level of precipitation. The height growth response to fertilization was best both in absolute terms and relative to control at high precipitation, whereas the response to thinning was less affected and in fact best relative to control at low precipitation. This relates well to the finding in the previous section which showed that the soil water potential was increased by thinning and consequently the precipitation requirement would diminish.

Conclusions

Present guidelines for forest fertilization are based on empirical growth trials which at best have attempted to relate responses to some measure of site nutrient status (e.g., foliar nutrient concentration), site index, stand age, and stand density. Few studies have related responses directly to climatic variables although indications are that they could be important. In thinning, the potential damage from wind and snow is usually taken into account in locations where this could be critical.

The best evidence for interaction of nitrogen fertilization with climatic variables pertains to the site water conditions as affected by precipitation. The studies done at the Pacific Forestry Centre on nitrogen fertilization and water interaction in growth of coastal Douglas-fir are reviewed. One study demonstrated a substantial interaction between nitrogen fertilization and irrigation but it needs to be shown how this will depend on the degree of water and nitrogen deficiency on a site. Nitrogen fertilization had no significant effect on soil and tree water potential so this treatment would not aggravate site water conditions and thereby growth. On the other hand, stand thinning increased the soil water potential and this was shown to improve height growth at the Shawnigan site compared with control in years with below-normal June precipitation. Precipitation in this month, however, was very important for height growth response to fertilization; the best response both in absolute terms and relative to control occurred when precipitation exceeded the normal 40 mm.

Temperature can influence response to fertilization in many ways associated with nutrient availability, uptake, and utilization, but field trials of relationships of temperature to growth are lacking. One interesting aspect is that although the season of growth in the coastal Douglas-fir Pacific region is limited to less than one-half of the year (4 mo at Shawnigan), the temperature in most of the remaining year is mild enough to permit significant rates of photosynthesis (Waring and Franklin 1979). More consideration should therefore be given to climatic conditions during the dormant season and to the subsequent effects on growth. Regarding nitrogen fertilization, we should investigate whether an improved nitrogen status provides for an increase in photosynthate production in the dormant season. It has been shown that this treatment increases the photosynthetic capacity throughout this season when measured under optimum light and temperature (Brix 1971, 1983), but the benefit of improved nutrition is not evident at low light intensity (Brix 1971). We therefore need to record both light and temperature to clarify how nitrogen fertilization might influence carbohydrate production during the dormant season.

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Use of Meteorology in Forest Fire Decision Support Systems

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Abstract

Modern forest fire management centers such as those presently being established in each of Ontario's five northern forest regions have meteorological requirements significantly different from those of traditional fire control organizations. Such a center must reliably and opportunely anticipate likely fire occurrence and fire behavior for an area at least the size of the province of New Brunswick. Key to the success of these centers is the quality and quantity of meteorological inputs. Historical weather and the present meteorological state of the region are best determined through the fire center's own weather stations network and real-time lightning and precipitation radar sensors. Forecasts of future weather conditions must continue to be made either by the national weather service or by fire center meteorologists having access to the national weather database. More emphasis is required on forecasts of lightning and precipitation locations and amounts. New requirements include forecast of atmospheric visibility and stability, hourly changes in basic weather factors, and measures of forecast uncertainty. New approaches to the support of these fire management centers will be required by the weather service.

Résumé

Les nouveaux centres de gestion des incendies de forêt, comme ceux qu'on établit actuellement dans chacune des cinq régions forestières du nord de l'Ontario, ont des besoins météorologiques bien différents de ceux des organismes traditionnels de lutte contre les incendies. Les nouveaux centres doivent prévoir avec fiabilité et au moment opportun la manifestation et le comportement probables d'un incendie pour une région dont la superficie est au moins équivalente à celle du Nouveau-Brunswick. La clé du succès de ces centres réside dans la qualité et la quantité des entrées météorologiques. La meilleure façon de déterminer le climat historique et les conditions météorologiques actuelles consiste à utiliser le réseau de stations météorologiques et les détecteurs de radars de précipitations et d'éclairs en temps réel du centre d'incendie. Le service national d'observations météorologiques ou les météorologistes du centre d'incendie, qui ont accès à la banque nationale de données météorologiques, doivent continuer à prévoir les conditions atmosphériques futures. On doit accorder plus d'importance à la prévision de l'emplacement et des valeurs quantitatives d'éclairs et de précipitations. Les nouvelles exigences comprennent les prévisions de visibilité et de stabilité atmosphérique ainsi que de l'évolution des facteurs météorologiques fondamentaux d'heure en heure, et la mesure du degré d'incertitude des prévisions. Le service d'observations météorologiques devra recourir à des approches innovatrices pour aider les nouveaux centres de gestion des incendies.

The Minisonde as a Management Tool in Planning and Conducting a Prescribed Burn

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Abstract

The study of the relationship of upper winds and lapse rates to show how a fire behaves will assist the Fire Behavior Specialist to better plan all aspects of the prescribed burn. The approach in this study is empirical and apparently it will be ongoing for many years. The discussion presented in this paper is an introduction only, and the results and conclusions should be scrutinized carefully.

Résumé

L'étude de la relation entre les vents en altitude et les gradients thermiques verticaux en vue de montrer le comportement d'un incendie aidera les spécialistes du domaine à mieux prévoir tous les aspects d'un brûlage dirigé. L'approche de cette étude qui, semble-t-il, s'étendra sur de nombreuses années, est empirique. Le présent exposé n'est qu'une introduction, et les résultats ainsi que les conclusions devraient être soumis à un examen approfondi.

Introduction

Upper air data for the fire behavior model has for many years been, as a result of necessity, obtained from upper air observing stations operated by government agencies in both Canada and the United States. These observing stations are part of a worldwide network of such stations. Two observations are taken daily and simultaneously by each station at 0000 UTC and 1200 UTC. During the summer months, when daylight saving time is in effect, this translates to 0800 and 2000 local time in the eastern time zone, of both Canada and the United States.

For most prescribed burns (P.B.) conducted by the Ontario Ministry of Natural Resources (OMNR), these times of observations are inappropriate. Most P.B.'s are now ignited between the hours of 1300 and 1900 local time.

Temperature and wind in that portion of the atmosphere lying generally below 2000 m undergo rather large diurnal changes in values. Obviously, upper air data gathered at 0800 can be of little use, or even misleading, in predicting fire behavior for a P.B. being ignited at, say, 1600, after 8 h of atmosphere modification.

Also of concern is the need to extrapolate the data from these sites, often over a distance of several hundred kilometers to the P.B. site, as is often the case in Canada. When a frontal zone exists between the two locations this often proves impractical.

We will look at a typical minisonde as it pertains to P.B. operations to see what it does and how its portability overcomes the problems of space and time that are part of the standard upper air network.

The Minisonde

The minisonde system used by the OMNR consists of six major parts:

1. The airborne radio transmitter with integrated temperature sensor.
2. Balloon to carry transmitter aloft.
3. Radio receiver and processor.
4. Printer. Manufacturer Aero-Aqua Inc., Markham, Ontario.
5. Balloon tracking theodolite. Manufacturer Breithaupt, West Germany.
6. Sharp 1500A hand-held computer.

The transmitter is powered by a small 9-Volt transistor radio type battery. The receiver and printer both contain (rechargeable) high capacity gel batteries that can operate the equipment for at least 3 d of normal operations.

A vehicle to house the equipment and from which to operate it provides the required portability. Upper air soundings can be taken within a mile or two of the P.B. site and at the time that is most appropriate for obtaining the necessary information.

The balloon is inflated sufficiently to lift the transmitter at a rate of 180 m/min. The recording chart is driven at a constant speed. It is therefore easy to analyze the chart as a graph with a temperature along the "x" axis and height as the "y" axis.

A specially designed theodolite for tracking balloons is part of the minisonde package. It is used to take readings of azimuth and elevation of the balloon during each minute of ascent. From these values and the known rate of ascent the upper wind speed and direction are calculated.

Application

The minisonde as a management tool in the decision-making process has its greatest application in the P.B. program rather than in wildfire situations. For example, the first and most important decision that has to be made by the person in charge of a prescribed burn (the Fire Boss) is whether or not to ignite the fire. This decision is not an option to the Fire Boss on a wildfire except in burn out operations.

As the operations for the two different fire types are studied further it becomes obvious that the minisonde can be used in making more decisions in conducting a P.B. than a wildfire. However, although the scope in which the minisonde is used in the wildfire situation is smaller, it is by no means less important. This is especially true in providing the fire crews and base camp personnel the highest possible degree of safety while performing their duties.

The following are some of the most common questions a Fire Boss must answer, or decisions he must make before conducting a P.B.

a) Can the P.B. be conducted effectively and safely under the present and forecast weather conditions?

b) How will the smoke affect air support operations around the fire during ignition and later during possible suppression operations?

c) Will local smoke-sensitive areas, i.e., airports, cities, etc., be affected?

d) What will be the spotting potential as a result of the upper level wind speed and direction?

e) How vigorous will be the convective column and the resulting fire intensity?

f) Will the convective column be conducive to extreme fire whirl generation?

These questions are best answered after analysis of the upper air data in terms of stability and wind profile in a time frame of 1 h or less before time of ignition.

The method of using this data in problem-solving in OMNR fire operations is still quite subjective, and to some small extent, intuitive as a consequence of previous experiences. The relationship of fire behavior and associated wind profiles from the study "Atmospheric Conditions Related to Blow-up Fires" (Byram 1954) is used presently as a basis for some predictions. This study is undergoing constant scrutiny as part of the OMNR minisonde program.

As far as stability is concerned, it has been found that severe whirlwinds occur most often when winds are 15 kph or less through the lower 1000–1500 m of the atmosphere with a lapse rate close to or greater than 1°C per 100 m through that same depth. This layer is usually capped by a stable layer of at least 500 m.

For center fire ignition, an unstable layer from the surface to at least 600 m is required, with a shallow layer next to the surface having a lapse rate greater than 1°C per 100 m. This lower layer is usually in the order of 15–20 m in depth. The winds are most often 15–20 kph or less below 600 m dropping to less than 10 kph at the surface.

It has also been found that a temperature change of as little as 3°C at the surface can significantly alter the smoke column and consequently fire intensity in small fires where smoke column tops are below 2000 m.

Conclusion

I feel that the experience gained from this present program will enhance the mathematical models now present, and aid in the development of new models. These will further describe fire behavior in more detailed and subtle terms than has previously been possible when less accurate upper air data was used.

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Eastern Spruce Budworm Larval Development and Behavior, Adult Dispersal, and Efficacy of Control Methods

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Abstract

This paper reviews the climatic factors related to eastern spruce budworm, *Choristoneura fumiferana* (Clem.), epidemics in Eastern Canada, specifically regarding larval development and behavior, the attendant efficacy of current methods of population control, and dispersal characteristics of the adult moth. Larvae normally molt to become third instars in late May, shortly after which the insects occupy a habitat where they become vulnerable to chemical and biological insecticides. The relative phenology of this development may be compressed in time under predominantly marine flow conditions, thus posing problems for adequate areal coverage with insecticides. Control efficacy is related to the effectiveness of delivery to the forest canopy which, contrary to widely accepted belief, now appears lowest under stable, light wind conditions, unless the spraying aircraft fly near the forest canopy. Studies in progress show the relative frequency and time of day that certain categories of spray weather may be expected. Immediate and later postspray weather, particularly as it affects larval behavior, also relates to control efficacy. Redistribution of spruce budworm populations, accomplished during the adult moth stage in July, is strongly controlled by temperature and winds in the lower few hundred metres during the evenings.

Résumé

Cet exposé examine les facteurs climatiques liés aux infestations de la tordeuse des bourgeons de l'épinette, *Choristoneura fumiferana* (Clem.), dans l'est du Canada, surtout sous l'aspect du développement et du comportement larvaires, de l'efficacité correspondante des méthodes actuelles de répression des populations, ainsi que des caractéristiques de dispersion de l'insecte adulte. Les larves atteignent habituellement le troisième stade larvaire à la fin de mai et occupent peu après un habitat où elles deviennent vulnérables aux insecticides chimiques et biologiques. La phénologie relative de ce développement peut être comprimée dans le temps dans des conditions de circulation marine prédominantes, nuisant ainsi à la pulvérisation adéquate d'insecticides sur les zones infestées. L'efficacité de la lutte contre les ravageurs est liée à celle de l'épandage des insecticides sur le couvert de la forêt qui, contrairement à la croyance générale, semble être minimale dans des conditions stables par vent léger, à moins que l'avion citerne ne vole très près du couvert. Des études en cours montrent la fréquence relative de certaines catégories de conditions atmosphériques favorables aux pulvérisations ainsi que l'heure du jour à laquelle elles peuvent survenir. L'efficacité de la lutte contre les ravageurs est également liée aux conditions atmosphériques immédiatement après la pulvérisation ainsi qu'ultérieurement, surtout en ce qui concerne leur effet sur le comportement des larves. La redistribution des populations de tordeuses des bourgeons de l'épinette, qui a lieu pendant la période de vie adulte de l'insecte en juillet, est fortement déterminée par les vents saisonniers qui soufflent dans les quelques centaines de mètres inférieurs en soirée.

Introduction

The eastern spruce budworm, *Choristoneura fumiferana* (Clem.), is the most formidable insect foe of Canadian coniferous forests (Prebble 1975). Appropriately, the insect has been the subject of major research programs, focusing progressively on its epidemiology (Morris 1963), adult dispersal (Greenbank et al. 1980), and the efficacy of aerial spray programs (Shea and Nigam 1984) and their environmental consequences (Varty 1980). Sanders et al. (1985) summarized recent advances in research within the collaborative CANUSA (Canada–United States Spruce Budworms) Program. Weather factors are intrinsic in all phases of the spruce budworm problem, and meteorological research has thus been an important component of these programs. This paper will review the findings of this research regarding larval development and behavior, adult dispersal, and the efficacy of control by aerial spraying, as well as the implications of the research to pest management.

Larval Development and Behavior

The life cycle of the spruce budworm is completed in 12 mo, overlapping 2 calendar yr (Miller 1963, Talerico 1984). Small larvae emerge from eggs in late July and August, 8–12 d after oviposition. These first-instar larvae do not feed, but disperse through the stand to seek suitable overwintering habitats on trees of host species. They may drop from branches on silken threads, and may be wind-dispersed within or beyond the stand. They spin hibernacula, mostly in bark crevices on the branches, within which they molt to second-instar larvae and overwinter in diapause. The insects remain inactive until about late April, when during spring warming they emerge and begin active feeding, first mining the needles of old foliage then newly swollen buds. By mid-June they have molted to fifth- and sixth-instar larvae and begin to feed voraciously on the current year's foliage. Fully grown sixth-instar spruce budworm larvae measure 18–24 mm long. Around the end of June they enter a pupal stage which lasts 8–12 d, before emerging as adult moths to recommence the cycle.

Although weather affects all stages of development, this section will deal only with larval development during spring, focusing on the late larval instars when the insect feeds most heavily.

Spring emergence begins when sufficient heat units have been accumulated, and the survival and development thereafter become of critical concern to the forest manager because it is the period of active feeding. Feeding rate, too, becomes a weather-influenced factor, closely tied in with the codevelopment of the host foliage. The most practical application of knowledge of development rate relationships, however, has been in the planning of the control operations. The main basis for calculating emergence and development has been the heat unit (degree-day) method. Early work (Bean 1961) suggested a development threshold temperature of 37°F (2.8°C), but studies in New Brunswick by Miller et al. (1971) found 42°F (5.6°C) to be a more appropriate temperature. MacNutt (1985) found the 5°C base commonly provided in climatological publications to be almost identical with the 42°F base in accounting for explained variance. Heat unit relationships developed from field data at different locations, for emergence and for the peak occurrence of subsequent development stages, have been found to differ to an extent that is slight but statistically significant (Bean and Wilson 1964, Lim 1983, MacNutt 1985, Miller et al. 1971). If one postulates that development is inhibited above some upper threshold (which Miller et al. 1971 suggest is 78°F or 25.6°C), and considers that the internal temperature of the budworm may be more than 3°C above ambient temperature (Wellington 1950), the relative frequency of occurrence of high temperature at different locations could partly account for the difference in development. The relative representativeness of the locations of the temperature measurements is, of course, another important consideration in comparing results from different studies.

In MacNutt's (1985) study, development of larvae was monitored separately on balsam fir and spruces (red and black), and related to temperature at a nearby standard climatological station. The critical third-instar stage of development, when insecticides can first be brought into contact with the insects, was reached an average of 19 Celsius degree-days earlier on fir than on spruce, and the end of the period of effective control (fifth instar), before heaviest feeding begins (Shea and Nigam 1984), was reached 31 degree-days earlier. For the different species, these represent differences of 2–3 d which have to be taken into account in the tactical planning for protection of mixed spruce-fir forests. In current operational practice each spray block is treated twice, at intervals to allow for differences in development.

Spraying operations in New Brunswick are scheduled to shift from one zone to another as larval development reaches the third instar. Zones have been selected to represent normal time lags of $2\frac{1}{2}$ d between zones, but the normal development pattern may be altered in a particular year. In 1979, for example, a period of continued easterly flows retarded development in eastern and central New Brunswick and allowed development in the northwestern part of the province to advance normally, so that late larval stages were reached at about the same time. Such abnormal weather situations pose serious problems in protecting the forest against foliage loss.

Development variations may occur between different feeding sites, particularly during sunny weather. When exposed to direct solar insolation, male cones of balsam fir, for example, warm up more rapidly and retain heat longer than do needles or vegetative buds. Also, temperatures at midday average 2–3°C warmer on the south sides of the canopies than on the north sides. On the other hand, under cloudy conditions the temperature tends towards uniformity at all feeding sites. Accordingly, in generally wet or overcast springs, larval development proceeds at nearly the same rate at all feeding sites in a given area, whereas dry, sunny springs result in increased developmental rates in larvae occupying warmer sites, such as male cones (Greenbank 1963).

Temperature also affects the feeding habits of the insects. Evidence suggests that without strong insolation, larvae do not feed at temperatures below 10°C. Such a checking effect of temperature on feeding would be most pronounced in the second instar, immediately after emergence, when temperature would tend to be lowest. The effect would diminish with each successive instar, since temperatures would be warming with the approach and arrival of summer (Wellington and Henson 1947). The mining practice of feeding budworm larvae, described by Atwood (1944), may lessen somewhat the impact of cool temperatures. Under clear, sunny conditions, direct insolation may sufficiently warm the foliage enclosing the larvae to allow feeding at air temperatures below 10°C (Wellington and Henson 1947).

Recent technology now allows a more rigorous approach to field studies of larval behavior. The presence of a human observer will cause feeding larvae to retreat to their silken habitat (Nigam, pers. comm. 1985); so in a current study in New Brunswick individual insects are being monitored by high-magnification surveillance video cameras at several microhabitat sites, where canopy temperatures are being simultaneously measured, at a location where several other meteorological parameters are being measured.

This research will assist protection agencies in scheduling insecticide applications at times when the larvae are most susceptible, in relation to development stages and feeding behavior. It has been thought that larvae must forage outside their microhabitat to be effectively exposed (Varty and Godin 1983); since that behavior is weather related, an understanding of the relationship will allow anticipated weather conditions to be incorporated more effectively into the planning.

Meanwhile, some doubt had been cast on the protection afforded to inactive larvae sheltered within their microhabitat. Video-camera records have revealed that very small droplets (diameters <10 µm) of insecticide may penetrate the microhabitat (Nigam, pers. comm. 1986). Effort to design methods of eliminating very small droplets from the emission spectrum of spray nozzles may therefore be counterproductive, although from an environmental point of view these droplets account for undesirable long-range drift.

Adult Dispersal

Emergence of spruce budworm moths from pupae occurs over 10–15 d at any one site (Sanders 1975), usually in early July over most of New Brunswick. They live for about 10 d. Females mate and lay up to 50% of their eggs within 2 d, then begin a period of very active emigration flights (Greenbank et al. 1980).

It had long been known that spruce budworm moths are transported considerable distances; records of massive moth invasions dating back to 1909 have been associated with the passage of cold fronts (Greenbank 1957). However, it was not until observations were made from towers above the forest canopy that the true extent of moth dispersal was appreciated (Greenbank 1973). Each evening, large numbers of moths were seen taking off and rising steeply above the forest canopy. Subsequent observations from a helicopter and light aircraft around dusk confirmed that large numbers of moths were in the air. These observations led to a

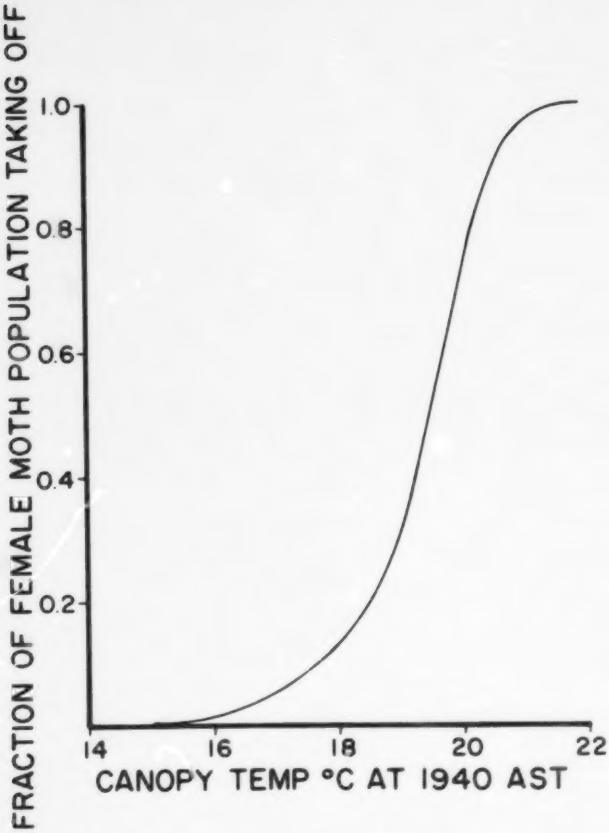

FIG. 1. Cumulative fractions of female eastern spruce budworm, *Choristoneura fumiferana* (Clem.), moth take-offs in relation to temperature at 2000 h local standard time. (Courtesy Maritimes Forest Centre, Canadian Forestry Service)

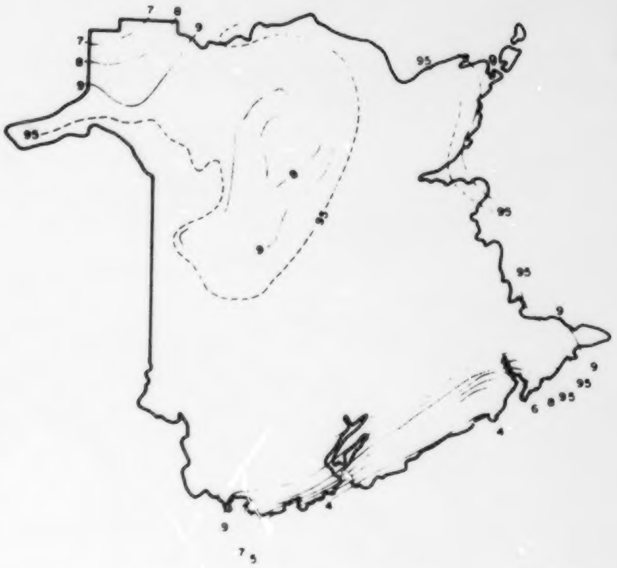

FIG. 2. Geographical distribution of the probability of suitable Maritimes' temperature for spruce budworm moth exodus, for any 6-d period during July.

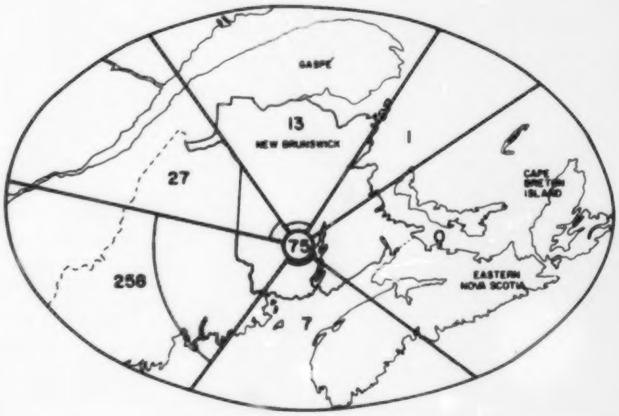

FIG. 3. Frequency of occurrence of wind-flows within specified sector over south/central New Brunswick, during 586 July evenings with temperatures favorable for spruce budworm moth exodus, 1958–76. The figure in the center of the circle represents the frequency of light/variable wind conditions. On the remaining 199 evenings temperatures were too cool for exodus flights.

multidisciplinary project in New Brunswick carried out between 1973 and 1976 (Greenbank et al. 1980), involving the use of ground-based and airborne radars to measure densities of airborne moth populations. Aircraft equipped with Doppler radar for precise navigation to measure drift and groundspeed were used to determine low-level wind-fields.

Moth take-off and exodus occur almost exclusively over a short period at dusk (Greenbank et al. 1980), apparently controlled by diminishing light but suppressed by temperatures below about 18°C (Fig. 1). This suggests a population "trapping" effect in regions such as higher elevations where evening temperature frequently declines too far before the declining light triggers take-off (Fig. 2). Where evening temperatures are marginally favorable, this also means that subsequent emigration is effectively constrained to certain wind directions (Fig. 3), thus limiting the effective spread of epidemics westward from the Atlantic coastal regions.

On typical nights, mean heights of flight are 200–250 m (Schaefer 1976), but on evenings with disturbed weather the mean height may be twice as great (Dickison et al. 1986), some moths reaching 1300 m (Greenbank et al. 1980). Typically, the moths remain airborne for 1$\frac{1}{2}$ h or more (Clark 1979), but on certain occasions the flight time is extended to 4 h or more. For example, moths have apparently crossed the Gulf of St. Lawrence to Newfoundland, requiring a flight time of 7–9 h (Greenbank et al. 1980).

Mesoscale weather systems, for example, fronts and sea breezes (Neumann and Mukammal 1981, Rainey 1979, Schaefer 1976), with their attendant convergence cause airborne moths to be concentrated in space. This was seen as providing an opportunity to limit the spread of epidemics by spraying airborne concentrations of egg-carrying moths (Kettela and Miller 1975), but the tactic (commonly used in locust control, Rainey 1976) has not been adopted operationally.

Efficacy of Control Methods

In the mid-1970s, it was considered that there was "no operationally available alternative to chemical insecticides" for protection of the spruce–fir forests in New Brunswick (Baskerville 1976). Meanwhile, the costs of these insecticides and biological alternatives (for example, *Bacillus thuringiensis* [B.t.]) and their delivery by aerial spraying were escalating, environmental concerns were great, and the forest blocks to be protected were increasingly segmented. There was an obvious need to achieve more precise and efficient spraying (Dixon and Irving 1985, Picot et al. 1986) and more efficacious biological control (Dimond 1985, Varty and Nigam 1985). Research directed at these needs has accelerated, under coordination of the New Brunswick Spray Efficacy Research Group (NBSERG). Meteorological factors are important considerations in most of the NBSERG component studies, focused mainly on field work near Dunphy airstrip in central New Brunswick, 90 km northeast of Fredericton (Crabbe et al. 1984).

Aerial spraying against spruce budworm has traditionally been carried out in the stable, light wind conditions of early morning and early evening. It was postulated, however, that more effective canopy penetration could be achieved by spraying in unstable conditions, and in turbulent conditions imposed by wind. Although testing of this hypothesis has shown that stable, light wind conditions did indeed not result in good canopy penetration (Crabbe 1985), the results have been confounded by other variables. Nozzle design and configuration, operating speed and wing loading, and especially flying height of the aircraft are more important than atmospheric stability in determining the effectiveness of canopy penetration of the spray cloud (Picot et al. 1986).

In the Dunphy spray trials the basic meteorological documentation (Crabbe et al. 1984) was provided by an array of temperature and wind sensors on a 46-m mast (extended to 63 m in 1986), operated during sequences of spray trials under simulated operational conditions using chemical simulants and tracers. Airborne concentrations (to at times 600-m altitude), canopy interception, and ground deposits were measured in an intensive grid extending as far as 1200 m from the spray line. In analyzing some of the early data from these trials, Crabbe (1985) noted that "surprisingly, turbulent wind conditions produce the lowest windborne loss to long-range drift . . . ." The 1982 and 1983 data were used to validate a droplet drift and deposition model (Picot et al. 1986) using categorical measures of stability, and mixing depths determined from either the tower data, tethersonde data, or minisonde data, and incorporating the effects on wake behavior of aircraft design and flying height. They concluded that "spraying should be done in conditions as near neutral as possible." Field data from 1986, now being analysed, do not seem to clarify the "best spray weather" question, affirming the need to use parametric models incorporating several variables in developing "best-deposit least-drift" scenarios.

If a prescribed stability condition can be determined, operational planning will be aided by a knowledge of the probable timing and duration of specified conditions. These probabilities are being determined from an extensive set of detailed minisonde data (Steeves and Dickison 1986), collected at the Dunphy site and elsewhere in New Brunswick. Although minisonde data are far less precise than those obtained from tower sensors, they extend to greater heights, thereby enabling the mixing depth to be determined. Furthermore, minisonde systems are highly mobile and can be employed for operational guidance and documentation.

Figure 4 shows the distribution of stability classes relative to sunrise and sunset. Stability is defined solely by lapse rate, for the layer 25–75 m above ground; "neutral" is arbitrarily defined as a lapse rate of 0.008–0.012°C/m. If neutral conditions are preferred, the analysis shows that the probability of occurrence is at a maximum 2–4 h after sunrise but can rarely be achieved in the evening as the transition from unstable to stable conditions occurs rapidly. The data used in the analysis are selective in that they have been collected only from late May to early July, and do not include periods with rain or very low ceilings. But budworm spraying operations are similarly restricted, so the selective data are appropriate for the intended use.

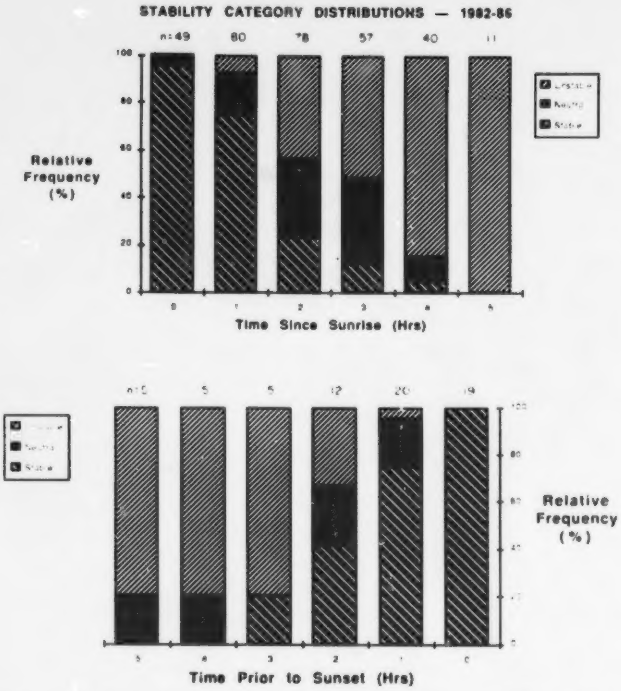

FIG. 4. Relative frequency of thermal stability categories after sunrise and before sunset in the layer 25–75 m above ground, from 381 atmospheric soundings conducted in central New Brunswick during late spring and early summer, 1982–86. ("Neutral" is arbitrarily defined as a lapse rate of 0.008–0.012°C/m.)

Summary

The eastern spruce budworm continues to be among the most extensively researched insects in the world. Its population dynamics, larval behavior, adult dispersal, and the attendant control operations are all strongly weather dependent. Consequently, the related research has an important meteorological component, which in recent years has involved the use of elaborate technology by the several agencies collaborating on field studies in New Brunswick. This paper has discussed the meteorological components of several of those projects, particularly those in which the University of New Brunswick Faculty of Forestry was involved.

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Air Pollution: Its Implications for Forest Productivity

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Abstract

It is widely understood that forests must be protected against fire and pests, but perhaps insufficiently appreciated that continued productivity depends on a particular blend of climate, air quality, soil, and other characteristics.

Air quality over extensive forest regions has become seriously impaired through the emissions of sulphur dioxide, nitrogen oxides, hydrocarbons, and potentially toxic metals. Subsequent atmospheric and other in situ reactions have generated a pollutant mix, the significance of which is far from being fully understood.

Adverse effects arise from direct damage to tree tissues, from indirect and cumulative effects on soil fertility, and from more complex interactions with other stresses, such as temperature, drought, and pests.

Although substantial pollutant-abatement measures are being implemented, the challenge facing forestry is to develop understanding and guides about required air-quality standards and management practices that will guarantee sustained productivity in a new and changing context. Of particular importance are climatic trends, exceptional climatic events, and the climate/air pollutant interaction.

Résumé

Il est généralement admis que les forêts doivent être protégées contre les incendies et les ravageurs, mais on ne tient peut-être pas suffisamment compte du fait qu'une productivité soutenue dépend d'un mélange particulier de facteurs climatiques, de qualité de l'air et du sol ainsi que d'autres caractéristiques.

La qualité de l'air au-dessus de vastes régions forestières s'est considérablement dégradée par suite des émissions d'anhydride sulfureux, d'oxydes d'azote, d'hydrocarbures et de métaux potentiellement toxiques. Des réactions atmosphériques et autres *in situ*, qui surviennent ultérieurement, ont produit un mélange polluant dont les conséquences sont loin d'être entièrement comprises.

Des répercussions défavorables résultent des dommages directs infligés aux tissus des arbres, des effets indirects et cumulatifs sur la fertilité du sol, ainsi que des interactions plus complexes avec d'autres contraintes comme la température, la sécheresse et les ravageurs.

Bien qu'on mette en application des mesures importantes de lutte contre la pollution, le défi à relever en foresterie consiste à faciliter la compréhension et à rédiger des guides de normes nécessaires sur la qualité de l'air et les méthodes de gestion, qui garantiront une productivité soutenue dans un nouveau contexte en évolution. Les tendances climatiques, les phénomènes climatiques exceptionnels et l'interaction entre les polluants atmosphériques et le climat revêtent une importance particulière.

Introduction

Within recent years a new threat to forests has arisen — acid rain, widely perceived as inflicting serious harm on waters and forests. Forests in Europe and North America are said to be declining and dying due to acid rain, and it is claimed by some to be the culprit responsible for the serious dieback currently affecting sugar maple (*Acer saccharum* Marsh.) in Eastern Canada.

Hypotheses abound concerning the way acid rain might affect forests — there were said to be 186 explanations at the last count (Pearce 1986) — ranging from mechanisms involving direct actions on tissues, indirect effects on soil, mechanisms operating in conjunction with traditional stresses such as drought and other exceptional climatic events, and last but by no means least mechanisms not involving air pollution at all (Rehfuess 1987).

Scrutiny of the European literature does not indicate fewer hypotheses, in fact, rather the reverse — an abandoning of early simplistic explanations for ones that give greater recognition to the processes, pathways, and linkages making up forest ecosystems.

What is the situation in Canada? Is much of the forest threatened? Is air pollution serious and getting worse? Is there evidence of climate/air pollution interaction? Is air pollution related in any way to the changing patterns of forest management? Is the long-term fertility of forest soils likely to be affected? This paper will attempt to answer these questions.

The Canadian Forest and Air Pollution Scenario

There are 10 major forest-vegetation regions in Canada (Figs 1 and 2). They are fully described by Rowe (1972), but for the purposes of this paper note that in Eastern Canada purely deciduous cover is restricted to the southernmost parts of Ontario. North of this in Ontario and throughout southern Quebec is the Great Lakes–St. Lawrence mixed-wood forest and north of this again stretching as an arc is the main boreal coniferous forest. In 1980, a harvest of 145 million m^3 was obtained from 760 000 ha, representing an average productivity of 1.9 m^3/ha/yr, assuming a 100-yr rotation.

From the chemical analysis of a network of precipitation gauges (Summers et al. 1986, Barrie and Sirois 1986), it has been possible to describe the extent to which Canadian forests are impacted by wet acid sulphate and nitrate. This is summarized in Table 1. Of the 161 million ha, 72% overall (83 in Manitoba westwards plus 32 in Ontario eastwards), are not exposed to significant levels of air pollution. This takes the 20-kg acid sulphate level as a threshold and assumes it is a rough guide for air pollution generally. However, the remaining 28% or 46 million ha that are so exposed, in British Columbia and in the East, are important forests near mills and markets. The 39 million ha of the total 71 million ha significantly exposed in the East are distributed across Southern Ontario and Quebec, the three Maritime provinces, and about half of Newfoundland. The 39 million ha take in all of the mixed-wood forest, most of the

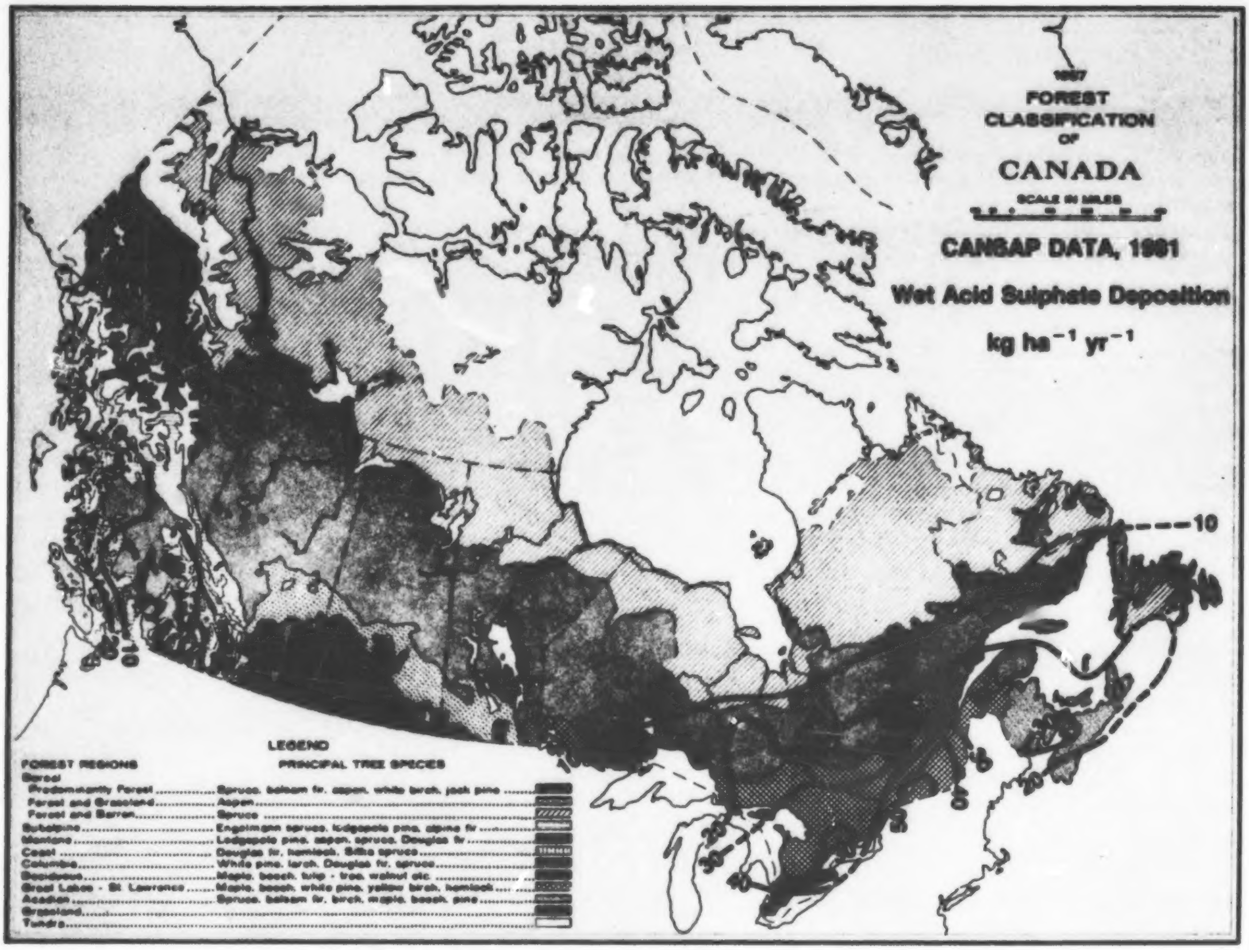

1957
FOREST
CLASSIFICATION
OF
CANADA
SCALE IN MILES
CANSAP DATA, 1981
Wet Acid Sulphate Deposition
kg ha⁻¹ yr⁻¹
10
10
LEGEND
FOREST REGIONS
PRINCIPAL TREE SPECIES
Boreal
Predominantly Forest .... Spruce, balsam fir, aspen, white birch, jack pine
Forest and Grassland .... Aspen
Forest and Barren .... Spruce
Subalpine .... Engelmann spruce, lodgepole pine, alpine fir
Montane .... Lodgepole pine, aspen, spruce, Douglas fir
Coast .... Douglas fir, hemlock, Sitka spruce
Columbia .... White pine, larch, Douglas fir, spruce
Deciduous .... Maple, beech, tulip - tree, walnut etc.
Great Lakes - St. Lawrence .... Maple, beech, white pine, yellow birch, hemlock
Acadian .... Spruce, balsam fir, birch, maple, beech, pine
Grassland ....
Tundra ....

FIG. 1. Forest classification of Canada indicating acid sulphate deposition contours.

TABLE 1. Acid sulphate deposition and Canadian forests — productive and accessible forest (millions of hectares).

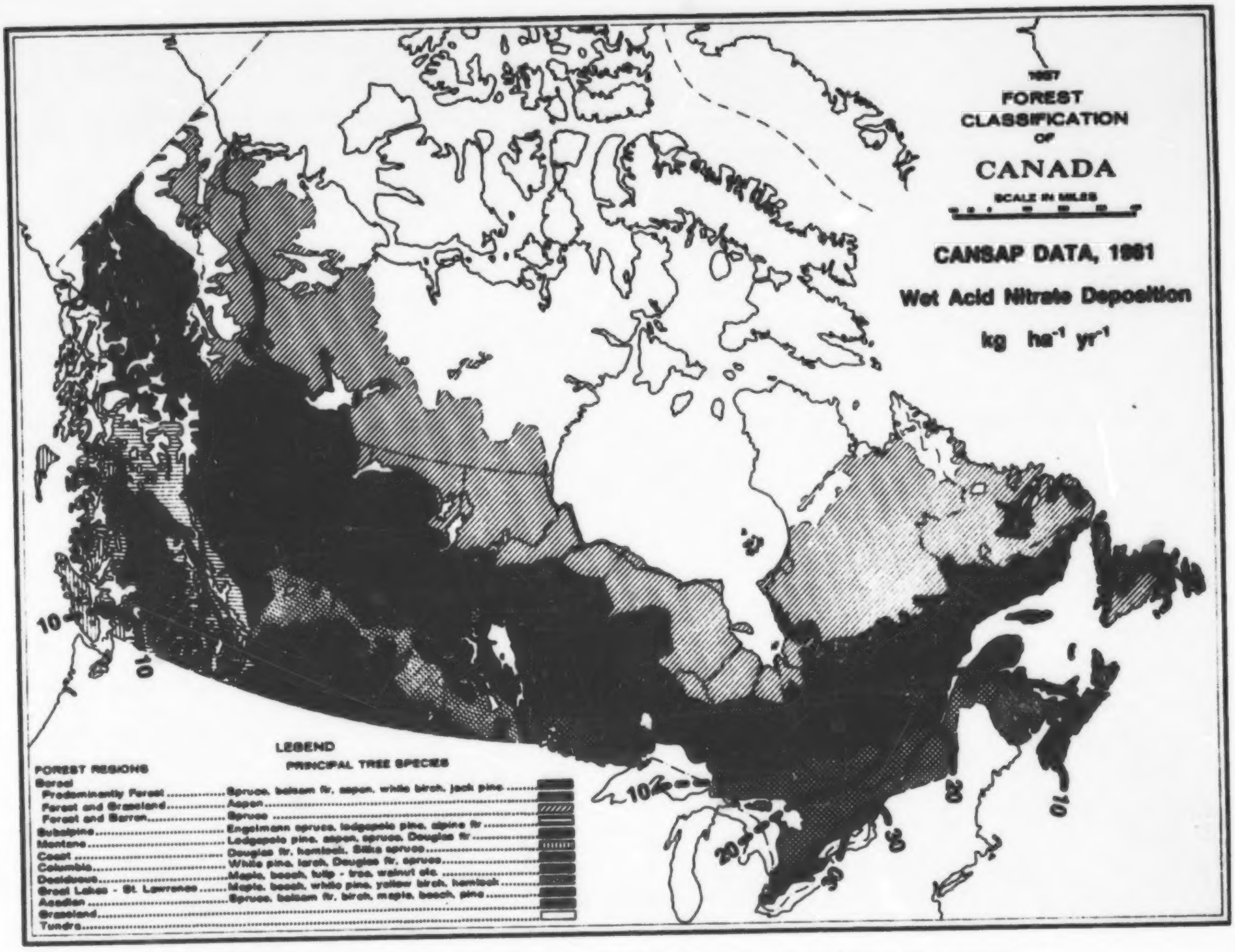
Deposition rate	Canada	Manitoba westwards	Ontario eastwards
all rates	161	90(56%)	71(44%)
< 20 kg $SO_4ha^{-1}yr^{-1}$	115	83	32
> 20 kg $SO_4ha^{-1}yr^{-1}$	46	7	39
% of forest polluted by acid SO_4	28	8	55

Acadian forest south of the St. Lawrence River, and appreciable areas of the boreal forest (Fig. 1).

In southwest Ontario and southeast Quebec deposition levels exceed 20 kg and to all "wet" values must be added another 25% for so-called "dry" deposition entrapped by a forest canopy. In Western Canada about 7 million ha based on Vancouver Island and on part of the Coast Range received a similar deposition. However, the 20-kg level is a threshold for forest ecosystem change and for lake acidification on moderately sensitive terrain: it is not necessarily a threshold for forest injury.

Regarding the distribution of injurious ambient concentrations of air pollutants in Canadian forests, the situation today appears to be that apart from essentially local problems with mainly sulphur dioxide near strong point-emitters, the most serious regional problem centers on ozone and perhaps on poorly characterized mixtures of air pollutants. For ozone, rural monitors have been lacking, but we know that episodes of phytotoxic concentrations occur in Southern Canada, in New Brunswick, in the greater Vancouver area, and possibly elsewhere. The more southerly mixed-wood Canadian forests may be experiencing adverse concentrations of ozone from time to time combined with a fairly continuous deposition of acid precipitation. Recently published hourly concentrations for mountain-top, slope, and plains situations in Alberta are 37, 28, and 26 ppb, respectively (Angle and Sandhu 1986), while seasonal mean concentrations at three sites in Quebec were 40 ppb (Roundtop Mt., 845 m), 34 ppb (Mt. Tremblant, 860 m), 29 ppb (Montmorency, 970 m), and 23 ppb (valley site, 250 m) (Schemenauer and Anlauf 1987).

Since 1980 the eastern hardwood forests have also shown


1957
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Grassland
Tundra

FIG. 2. Forest classification of Canada indicating acid nitrate deposition contours.

TABLE 2. Reductions in air-pollutant emissions in the United States (Anon. 1985).

Pollutant	Annual emissions (millions of tonnes) 1977	1983	% reductions
SO_2	26.3	20.8	20.9
NO_x	20.9	19.4	7.2
VOC	23.6	19.9	15.7

very serious decline, and there is much debate on possible relationships. There are also cases in the same general area where conifers show a chlorosis somewhat reminiscent of that seen in Central Europe, although this is confounded by chlorosis on outwash sands being observed for many years due to potassium deficiency. Nonetheless, this raises particular concern because whereas sulphur dioxide emissions have been dropping appreciably in both Canada and the United States, there is less downward movement for nitrogen oxides and volatile organics — the precursors of ozone (Table 2).

Air Pollution Trends

The Canadian federal government, in collaboration with provincial governments, industry, and the United States government, is implementing several important measures that will change the current air-pollution picture (Manson 1985).

The first of these focuses on sulphur dioxide, the principal precursor of acid rain, and is driven by the availability of evidence that links lake acidification on sensitive terrain with the degree of acid precipitation. It has been estimated that lakes on moderately sensitive terrain will not further acidify if acid sulphate deposition can be kept below 20 kg per hectare per year (Glass et al. 1980), and a modeling calculation based on the assumed linear relation between regional emissions deposition suggests that a 50% cut in current regional emissions in the northeastern parts of the continent will reduce acid deposition to an acceptable level (Table 3). The limitations are that the Canadian reductions of 50% to be achieved by 1984 are not currently being matched by comparable United States cuts and that nowhere in the calculations enter aspects of suitability of the 20-kg standard for forest trees or soils. The standard may be adequate or inadequate. Overall, however, because sulphur

TABLE 3. Estimated acid sulphate depositions according to different abatement scenarios.

	Wet acid sulphate deposition ($\text{kg ha}^{-1}\text{yr}^{-1}$)		
	Current 1985	After 50% Canadian reduction	After 50% Canadian & 50% U.S. reduction
North-central Ontario	18–22	16–22	11–15
South-central Ontario	29–35	24–30	13–19
Southern Quebec	27–33	23–29	15–21
Southern Nova Scotia	17–23	16–22	15–20

dioxide emissions are decreasing in both Canada and the United States, an appreciable reduction in acid sulphate deposition can be expected.

A second major step is the implementation of tighter automobile emission standards. From 1988 onwards new cars will emit only 1.0, 0.4, and 3.4 g/mile of nitrogen oxides, hydrocarbons, and carbon monoxide respectively, representing major reductions from existing values of 3.1, 2.0, and 25.0 g/mile. These new standards parallel those stipulated in the United States and are among the most stringent in the world, nitrogen oxides, for example, being from 1.5 to 3.0 times more stringent than the new European Economic Community (EEC) standards. It is expected the new standards will reduce not only acid deposition but also the frequency of occurrence of injurious ozone episodes. However, because approximately one-half of NO_x emissions in the United States are generated from stationary sources, and VOC emissions are still considerable, the difficulties obstructing a reduction in ozone levels remain formidable.

From the Canadian forest-resource viewpoint, therefore, the future air-pollution scenario appears as follows. First, there is not a precise picture of actual pollutants present or in what concentrations, but there is better information for sulphate and nitrate deposition and ambient sulphur dioxide concentrations than for ozone, VOCs, and heavy metals. Secondly, there is not so much concern at present for deposited nitrate as in Central Europe (Rehfuess et al. 1983) because of the markedly lower levels (Fig. 2) and the good responses still obtainable from nitrogen fertilization (Weetman et al. 1987). Thirdly, there is considerable concern for the continued acid sulphate deposition, partly because of its unknown effect on nutrient-poor soils. Fourthly, there is an unknown concern centered on poorly defined VOCs, partly through their phytotoxicity and partly through their role in ozone formation (Nikolaou et al. 1984, Kreuzig et al. 1986, Sawada and Totsuka 1986). And fifthly, a considerable concern focused on ozone, through the narrow range between background and phytotoxic concentrations, and the general difficulties met elsewhere in trying to reduce harmful concentrations.

Forest Declines and Air Pollution

The question to be addressed now is, what is the decline situation in Canada and how is it likely to develop?

The term "decline" has sometimes been used for a normal or cyclical decrease in annual incremental growth that has nothing to do with air pollution or other stresses. Fortunately, attempts are being made to clarify this misconception (Hornbeck et al. 1986, Federer and Hornbeck 1987, Hyink and Zedacker 1987, Sheffield and Cost 1987), one of the more rigorous analyses of long-continued trends being published for Scots pine and Norway spruce by Sweden in 1982 (Anon. 1982).

Again, high-elevation situations have been selected without taking into account the considerable research and understanding that is available on tree-limit fluctuations and the generally adverse and highly variable ecological characteristics of such marginal sites (Hansen-Bristow 1986, Marchand et al. 1986).

In Canada decline and dieback caused by a variety of pests could be incorrectly attributed were it not for the long-established Forest Insect and Disease Survey Organization regularly monitoring forest health for disorders. The organization's annual reports provide detailed accounts of forest disorders arising from a variety of causes (Kondo and Taylor 1986). These can often be attributable to readily identifiable organisms or to abiotic factors such as drought, frost, or strong-point sources of air pollution. There is, in addition, decline and dieback not so readily attributable, perhaps the most serious and challenging being the widespread dieback of yellow birch and other hardwoods occurring in Eastern Canada between 1930 and 1950 (Anon. 1953).

Recently, an examination of these annual reports for 1951 to 1985 for just Ontario generated the following occurrences of decline, dieback, and deteriorations. Organisms associated with the disorders were sometimes identified but in numerous cases these were only secondary pests, the primary triggering agent remaining obscure:

Deterioration of birch: 1951, 52, 53, 54, 67, and 68.
Maple dieback: 1958, 59, 50, 61, 84, and 185.
Deterioration of roadside maples: 1962, 63, 64, 65, 66, 67, and 68.
Maple decline: 1977, 80, 83, and 84.
Maple mortality: 1977.
Branch mortality of maple: 1969, 71, and 72.
Oak decline: 1977, 83, 84, and 85.
Branch dieback of oak: 1969, 70, 71, 74, 76, and 78.
Oak mortality: 1970, 71, 74, 78, 79, 80, and 84.
Hardwood decline: 1978, 79, and 85.
Ash dieback: 1984 and 85.
Beech bark cankers: 1963 and 85.
Beech decline: 1967.
Basswood branch cankers: 1963 and 67.
Branch mortality of poplars: 1972.
Branch mortality of mountain ash: 1971.
Dothichiza canker of Lombardy poplar: 1962, 66, and 74.
Drought: 1964, 76, 83 and 84.
Abiotic damage: 1969, 71, and 83.
Heavy seed crop: 1984.

None of these occurrences referred to regional air pollution, yet it is reasonable to suppose from the historical pattern of emissions in the northeast that some episodes of elevated sulphur dioxide and ozone concentrations did occur during the 35-yr (Gschwandtner et al. 1986). One might reasonably speculate that from 1951 to 1985 ambient concentrations of sulphur dioxide first increased then decreased, but may never have been high enough to generate strikingly visual foliar symptoms. The precursors of ozone, in contrast, were increasing more consistently, but again concentrations of ozone may never have been high enough to generate symptoms that would be strikingly obvious and distinct from other symptoms, especially if observers were not familiar with ozone symptoms and had no information on rural ambient concentrations. What cannot be dismissed, in light of our understanding of multiple-stress and the results of the National Crop Loss Assessment Network (NCLAN) (Adams et al. 1985), is the possibility that air pollution contributed to the phenomena of decline, dieback, and deterioration reported, without there being seen foliar symptoms obviously indicative of air pollution. Such a hypothesis — hidden physiological damage — is certainly not new and is one of the hypotheses invoked to explain the malaise in the central European forest (Rennie and Halstead 1977, Schütt and Cowling 1985). We now realize, too, that one of the summers (1976) preceding the onset of the more widespread west/central European forest decline was one of the driest recorded and was characterized by very high ozone concentrations; these two stresses acted together and had an initiating weakening effect, the repercussive effects of which manifested themselves throughout successive years.

Indeed, it is this more elusive, interactive, and significant effect of regional air pollution that is so difficult to detect. Strong ambient concentrations of air pollutants are readily measured, their effects on foliage are often striking and characteristic, and there are usually well-established threshold air-quality standards developed from much prior fumigation experimentation. Of intermediate complexity are air-pollution effects on soils. Ambient thresholds are inappropriate and long-term deposition processes are difficult to simulate using short-term lysimetric tests, so it becomes very difficult to develop acid-deposition ceilings for forest soils as has been done for water bodies on sensitive terrain.

The wealth of observational experience available from the main essentially coniferous forest regions of Canada does not so far indicate the occurrence of decline phenomena that cannot be explained by conventional causes. In this regard the Canadian coniferous forest environment much resembles that of central Sweden (Andersson 1986), pollution levels, soils, climate, and forest type all being similar.

For the more southerly parts of Canada, which again are more comparable to the southern parts of Sweden, the picture is not so bright. Serious dieback has been occurring in the sugar maple (*Acer saccharum* Marsh.) forests of Quebec and Ontario, and comparisons have been made to the central European situation. As might be expected, viewpoints on cause vary widely (Carrier 1986, Maple Producers 1986, McIlveen et al. 1986). Ontario sees the problem dating back to the 1900s, Quebec only to 1982, but both provinces agree on its present seriousness. Aerial surveys conducted in Quebec show that of 533 600 ha examined in 1985, 317 600 ha (or 60%) were healthy or little affected. Some 189 200 ha (35%) were lightly affected, 22 300 ha (4%) were moderately affected, and 4500 hectares (1%) were seriously affected. The worst affected area south of the St. Lawrence River Valley is centered on Thetford Mines, east of Montreal. In terms of economic and social significance, the problem is profound. There are 10 000 maple-syrup producers in Quebec deriving much of their livelihood from the 7.3–13.5 million L of syrup produced per year (1979–83). The annual value averages $40 million and Quebec production amounts to 89% of the Canadian total. The decline phenomenon not only reduces sap yield, but eliminates trees for future tapping and kills them in such a way as to render their wood unsuitable for saw-lumber or fuelwood. There is no proof that air pollution causes maple dieback, but Carrier (1986) eliminates several possible factors as single causes of dieback in favor of air pollution as the main suspect. McIlveen et al. (1986) believe that no single cause can be identified but point to a possible combination of several factors, such as defoliating insects, drought, other extreme climatic events, nutritional deficiencies, improper management, secondary root organisms and air pollution. Indeed, one of the Ontario investigators, D. McLaughlin (1986), has pointed out that the combination of certain extreme events experienced within the recent 8 yr 1976–83 is likely to occur once every 250 yr.

These unusual climatic events and climatic trends are so important in understanding decline and the elaboration of effective air-quality standards. Added to the well-developed discipline of tree-growth in relation to climate (Smith 1986) must be concepts of the significance of fluctuations (Wigley 1985) and the documentation of long-term annual trends for specific regions (Diaz 1986).

Returning to the present maple dieback problem, clearly complex aspects besides air pollution are vital for its understanding. An almost identical widespread dieback affected yellow birch (*Betula alleghansiensis* Britton) in much the same region from 1930 to 1950 (Anon. 1953, Balch 1944) and the careful descriptions of the symptoms (mortality of branches, crowns, whole trees; foliar chlorosis, cupping, reduced size, imbalanced nutrient content) are strikingly similar to those now reported for maple and for European beech (*Fagus sylvatica* L.) in West Germany (Schütt and Summerer 1983).

The problem in Canada is being actively researched and in addition to the implementation of abatement, fertilization is being tried experimentally as a remedy. This has been suggested because of the imbalanced foliar concentrations of nutrients and the promising results obtained for arresting decline in some West Germany stands (Hüttl and Wisniewski 1987).

Research Challenges

In principle the research challenge appears straightforward. Decision-makers and regulatory authorities are faced constantly with requests for improved air quality to safeguard against injury to human health and resource values. Abatement is costly, often technologically complex, and not amenable to clear-cut choices when a mix of air pollutants is involved with poorly develop dose/response relationships.

Sooner or later — and usually sooner — the scientist must indicate to the regulatory authority the air-quality standards that his/her particular receptor material or organism can tolerate. If this is not done the regulations will be formulated without consulting the scientist or to fulfill the needs of another resource interest.

These "standards" have been known by other terms, ambient gas concentrations, critical loadings, ect., but in principle every research program has to aim to generate information on the threshold characteristics of air quality that must not be exceeded over the long-term to permit sustained forest productivity.

In the classical situations of strong point-source and single air-pollutants, the task was less complex in that the ambient standards developed were designed to protect against a stress that was assumed to act only on the foliar tissues and during fumigation. Residual toxicity and other gaseous pollutants were not considered.

The challenge becomes more complex when cumulative residuals have to be considered, as with acid deposition or heavy metals on soil, and even more so when the phytotoxicity interacts over a protracted time scale with some other stress factor such as drought, low temperature, or nutritional imbalance.

Perhaps most difficult of all is the situation where there is no dramatic or obvious effect on growth, where foliar symptoms are absent, but where on ecological principles a stress is suspected. Much of the eastern Canadian coniferous forest falls into this category. Nothing is apparently wrong, but the atmosphere is polluted and changes are occurring in the podzolic soils that result in the additional mobilization of aluminum into lake water (Gorham et al. 1986).

Finally compounding the challenge, difficult as it already is, is the complication that forest-management practices are changing. First-growth forests have been almost completely harvested to be replaced by planned and managed second- and third-growth stands of far shorter rotation length and higher utilization standards (Handley 1985). Greater nutrient-demands are involved, with the potential to increase the acidification of the soil already occurring through acid deposition (Hallbäcken and Tamm 1986, Nilsson et al. 1982, Van Breeman et al. 1984, Nykvist and Rosen 1985).

Required air-quality characteristics or standards that are to have long-term value cannot be formulated unless the functioning of forest ecosystems is fairly well understood. A few quickie experiments with seedlings and simulated acid rain may quickly provide information on the dimensions of a threat in the short-term and under a narrow set of conditions, but such experiments cannot hope to simulate longer term considerations involving different growth phases, a range of climatic events, delayed physiological effects, changing forest practices, and perhaps altered soil nutrient status.

Not only, therefore, must studies on "effects" embrace the fuller aspects of ecosystem functioning, but they have to recognize that ecosystems and their management may have changed appreciably from a former state where there would have been some stability or equilibrium among the three components — atmosphere, soil, and forest cover. Perhaps the greatest obstacle facing many foresters is the assumption that because natural unexploited forests have existed for thousands of years in spite of a variety of hazards, exploited forests will go on existing in much the same way in the future.

Evidence from Central Europe shows how dangerous such assumptions can be. The atmosphere has become seriously polluted in ways not adequately understood, natural species have been replaced, management has been intensive and demanding, incremental growth has sometimes fallen off unsuspectedly, and soils often no longer have the nutrient status they once did (Ulrich et al. 1980, Schröter 1985, Hüttl and Wisniewski 1987, Rehfuess 1987). Characteristics of the environment have changed and in this new setting the forest may no longer be able to withstand the more extreme cyclical events that were formerly accommodated. The forest does not necessarily decline steadily and uniformally but can do so from tree to tree sporadically and spasmodically, according to genetic diversity, mutual competition, and spatial site differences.

The third challenge concerns remedial measures. The scientist is faced with demands for cures where dieback is particularly serious. Abatement can be suggested if dose/response studies have progressed sufficiently to indicate which pollutant should be reduced by what amount. Sometimes, however, studies are just beginning, and they may never be able to recapture the complexity of the specific environmental circumstances that triggered a widespread dieback, and in any case most of the forest may have died before abatement can be implemented.

Such a challenge reiterates the need for ecological knowledge. More resistant species or provenances may be planted, fertilizers may be applied on the basis of foliar and soil diagnoses, and predictions may be made from historical records about the frequency of occurrence of unusual climatic events and pest epidemics. The latter may not cure a particular disaster, but it provides the risk assessment associated with forest production conducted in a particular ecological and environmental context.

Canadian Research

In this section examples will show how these challenges are being met in the Air Pollution Program of the Canadian Forestry Service.

Two main problem areas are now recognized: first, the maple and other forest stands where there is obvious decline or unthriftiness of unknown cause; second, forest stands — both coniferous and hardwood — where there is also significant air pollution, but where there is as yet no measurable effect on growth.

Five main objectives have been selected for both situations with an important sixth objective — funding the cause and a remedy for maple decline — applicable to the first situation.

The five objectives are:

1. To elucidate pollutant deposition rates or ambient concentrations that must not be exceeded if the continued productivity and well-being of forests are to be assured. (This information is essential for designing abatement strategy.)
2. To quantify dose/response relationships for different tree species, soils, climates, and pollutants. (This objective embraces a variety of ecological conditions and mechanisms of action and is the key towards answering objective 1.)
3. To monitor forests regularly for disorders and incipient stress, especially in the context of changing pollutant levels and varying climatic events. (This serves as an early warning system and a check on the adequacy of abatement measures.)
4. To establish appropriate baselines for future comparisons. (These are essential if in the future we are to be in a position to measure changes in forest and soil properties.)
5. To analyze trends in annual increments of tree growth

over the past 50 yr or more to discover whether air-pollution effects can be detected and isolated from other influences, such as climate.

Space does not permit more than an outline of this $2 million/yr program described in greater detail elsewhere (Rennie 1986). Studies are conducted in both the field and laboratory from six centers across Canada. In three main forested catchments distributed across Eastern Canada, hydrologic and element budgets are being prepared (Foster et al. 1986). These provide a framework understanding of the movement of elements into and out of the systems. Such information is essential to follow the fate of added sulphate, nitrate, and potentially toxic metals. Laboratory studies include testing the effects of simulated acid rain on tree-seedling growth (Percy 1986), plant reproductive processes (Cox 1983), root-mycorrhizae development (Fortin 1985), rootlet mortality (Hutchinson et al. 1986), and cuticle integrity (Percy and Baker 1986).

Indirect studies with soils are testing the effects of acidification on nutrient drainage (Arp 1983, Rutherford et al. 1985), on the mobilization of aluminum (Arp and Ouimet 1986a), and on the speciation and relative toxicities of different complex aluminum ions to tree seedlings (Arp and Ouimet 1986b, Hutchinson et al. 1986). Soil-nitrogen and soil-sulphur transformations are the focus of other studies (Mahendrappa 1982, Maynard et al. 1984). A novel study is testing the effect of soil acidification and aluminum mobilization on balsam fir rootlet resistance to pathogens.

The third main area described earlier uses over 100 permanent sample plots established in representative Canadian forests. In addition to the regular monitoring by entomologists and pathologists of the Forest Insect and Disease Survey, foliar samples are being taken annually and soil samples at 5-yr intervals to characterize status and to detect changes. There is a special interest in the collaborative European study which is attempting to identify foliar physiological and biochemical parameters indicative of early pollution effects. At present, a symptomology text provides guidance (Malhotra and Blauel 1980).

The program, as a whole, is conducted collaboratively with meteorologists, hydrologists, fisheries biologists, and wildlife specialists of other federal departments and there is a special linkage to provincial government research programs. There are close ties to the studies of other countries, especially to the United States and West Germany, and the regular exchange of research reports is conducted with numerous countries and agencies.

The Canadian Forestry Service has been associated with the ECE International Collaborative Program (ICP) for monitoring and assessing forest damage since this program's inception, a special bilateral study of sugar-maple dieback has just been inaugurated with the United States Eastern Hardwood Research Cooperative, and for 2 yr forest scientists of Canada, Mexico, and the United States have been collaborating under the aegis of the North American Forestry Commission's Atmospheric Deposition Study Group. For a challenging problem calling for a variety of disciplinary contributions the greatest possible pooling of expertise is desirable.

Synthesis

Clearly, the Canadian forestry community lives in a time of great change and challenge. The forest is of considerable importance economically, environmentally, and socially, constituting Canada's single most important industrial activity.

Productivity has risen steadily over the years and the 1982 Framework for Forest Renewal Policy Statement envisages an increase in forest productivity of 40% by the year 2000. Not everyone shares such optimism (Hohol 1985) and the research support relative to the value of the resource is appreciably lower than in several other forested countries (Canadian Institute of Forestry 1987). Nevertheless, constructive changes are occurring.

The natural first-growth forests have been changed mostly to planned and managed second- and third-growth stands of far shorter rotation length and higher utilization standards (Handley 1985). Over $1250 million of federal, provincial, and industry funding is now being devoted to forest management and a rehabilitation strategy is being implemented to reforest insufficiently stocked land. Annual seedling production has risen from 200 to 600 million in the past 10 yr and site preparation, planting, and weeding are increasingly practiced (Barron 1985). Interest is being reexpressed in large-scale forest fertilization. There is still much to do in these areas (Pearse et al. 1986a, b), but substantial research programs are in place assisting with site rehabilitation and with such problems as fire and pests. The opportunity to improve genetic stock is being exploited. It seems unlikely that well-known conventional problems will curtail reasonable estimates of increased productivity.

Associated with this change in management could be concerns unrecognized by many, understood in principle only by others, or viewed as remote. The elimination of fire and the repeated harvesting of short-rotation stands are such, for ecological principles dictate that if fundamental changes are made in expectations from nutrient-poor northern forest soils, much understanding is called for to specify the inputs required to sustain productivity. These are not immediate problems, but rather difficult ones that require recognition and attention now if site impoverishment and lower biological productivity are not to become widespread (Mahendrappa et al. 1986, Kimmins 1987).

In a separate class are problems of unknown cause and threats of unknown dimensions. The widespread yellow birch dieback of 1930-50 and the present-day widespread dieback of sugar maple are problems of this nature. In both instances air pollutants could have a role but the degree of air pollution and the mix of pollutants are almost certainly not the same for these same eastern Canadian regions between the 1930s and 1980s.

It is not easy now to establish what the air-pollution levels of the 1930s might have been, but if present levels are contributing significantly to maple dieback, then there is a serious threat overhanging the 7 million ha of coniferous forest in the West exposed to significant levels of air pollution, and a corresponding threat to the 39 million ha of coniferous and mixed-wood forest in the East.

The challenges, then, are fivefold:

— **First,** to recognize that fundamental changes are occurring in the forest production system, or what may be called the "atmosphere/forest/soil" equilibrium. Forest management is changing in Canada, without the underpinning of ecological understanding necessary to permit optimum management or to comprehend forest-growth behavior.

— **Second,** to have the foresight to develop a sufficient knowledge of ecosystem functioning to be able to evaluate and deflate new stresses without having to tackle each crisis without such a foundation.

— **Third,** the forest scientist must become more aware of climate/air pollution interactions and indicate to the atmospheric scientist parameters of concern so that monitoring networks can be designed and data banks analyzed catering to the interests and protection of forest resources.

— **Fourth,** to develop dose/response relationships for potentially harmful air pollutants, taking into account their different forms (gaseous and nongaseous), the different mechanisms of action on tissues and on soil, the different regional conditions, and the different climatic characteristics.

— **Fifth,** arising from the fourth challenge, to indicate to regulatory authorities the air-quality characteristics required for sustained forest productivity. Clearly, such characteristics should accommodate any counter-balancing or ameliorative cultural measures that the forest scientist might develop and recommend implementing.

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Dry Deposition Measurements Over a Deciduous Forest in Southern Ontario

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Abstract

As part of the Long Range Transport of Air Pollutants program, a micrometeorological site has been established in a maple–aspen forest near Barrie, Ontario. Measurements of the eddy fluxes of ozone and sulfur dioxide as well as momentum heat and water vapor were made from a 43-m tower. These data, obtained during late summer 1985 and through early summer 1986, are presented along with calculated deposition velocities. Energy budget data will also be presented along with data from the continuous monitoring of meteorological parameters, ozone, sulfur dioxide, and particulate sulfate concentrations beginning midsummer 1985.

Résumé

On a établi au milieu d'une forêt d'érables et de peupliers faux-trembles, près de Barrie en Ontario, une station micrométéorologique dans le cadre du programme de transport à grande distance des polluants atmosphériques. De la tour de 43 m, on a mesuré les flux turbulents d'ozone et d'anhydride sulfureux ainsi que la chaleur de la quantité de mouvement et la vapeur d'eau. Ces données, recueillies à la fin de l'été 1985 et au début de l'été 1986, sont présentées avec les vitesses calculées de dépôt. Des données de bilan énergétique sont également fournies avec des données relevées dans le cadre de la surveillance permanente des paramètres météorologiques et des concentrations d'ozone, d'anhydride sulfureux et de particules de sulfate, qui a débuté au milieu de l'été 1985.

Forestry in a Changing Climate

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Abstract

Accelerating increase in atmospheric carbon dioxide and other gases resulting from industrial activity will lead to dramatic changes in climate in the 21st century. Foresters are confronted with the issue now because they plan and initiate operations that extend over many decades. Forest ecosystems are sensitive to climate, and the projected climatic scenarios suggest an increase in biological production. But empirical models that relate vegetation to climate indicate that a severe mismatch may develop between Canada's forest regions and the climatic regions they occupy. Fire, insect pests, diseases, and weeds will respond quickly and strongly to changes in climate, and under the currently projected scenarios may assume critical proportions in the forest sector. Nevertheless, the promise of increased biological productivity, through longer, warmer seasons, enhanced efficiency of water use by plant species, and carbon dioxide enrichment offers a significant challenge and opportunity to foresters equipped for intensive forest management.

Résumé

L'augmentation accélérée de la concentration atmosphérique de gaz carbonique et d'autres gaz produits par les activités industrielles modifiera le climat de façon radicale au XXI^{e} siècle. Cependant, les forestiers sont confrontés à ce problème, à l'heure actuelle, parce que les processus qu'ils planifient et mettent en oeuvre s'étendent sur plusieurs décennies. Les écosystèmes forestiers sont vulnérables au climat, et les scénarios climatiques projetés indiquent un accroissement de la production biologique. Toutefois, les modèles empiriques qui relient la végétation au climat laissent entrevoir l'apparition possible d'une incompatibilité grave entre les forêts du Canada et les zones climatiques qu'elles occupent. Les incendies, les insectes ravageurs, les maladies et les mauvaises herbes réagiront rapidement et fortement à des changements climatiques et, selon les scénarios actuellement projetés, pourraient prendre des proportions critiques dans le secteur forestier. Néanmoins, la promesse d'une productivité biologique accrue, à cause de saisons plus longues et plus chaudes, de l'efficacité accrue de l'utilisation de l'eau par les espèces végétales, ainsi que de l'enrichissement par le gaz carbonique, offre un défi de taille et des possibilités intéressantes pour les forestiers spécialisés dans une gestion forestière intensive.

Introduction

This paper examines the implications of climate change for forestry and the forest sector in Canada, and focuses specifically on the climate scenario predicted by Manabe and Stouffer (1980) for a doubling of preindustrial concentrations of atmospheric carbon dioxide. Recent advances in ice-core analysis (Zumbrunn et al. 1982) have yielded reliable estimates of the historic trend in concentrations of CO_2. The estimated preindustrial (ca. 1750 A.D.) level is about 275 parts per million by volume (ppmv) (Neftel et al. in press), compared with a present day concentration of close to 350 ppmv, that is, a 25% increase has already taken place. Forward projections are fraught with many uncertainties concerning the demand for energy, the continuing place of fossil fuels in energy supplies, and the proportions of released CO_2 remaining in the atmosphere. In addition, there is a growing realization that other radiatively active trace gases, such as methane, nitrous oxide, and chlorofluorocarbons, are increasing at rates approximating or greatly exceeding that of CO_2. These projections, combined with CO_2, lead to much earlier predictions of conditions equivalent to doubled CO_2, in the range of about 2010–2050 A.D. (Bolin et al. 1986), and place associated climate scenarios well within the life span of trees being planted in Canada today.

Direct Effects of Increasing CO_2

The rise in atmospheric CO_2 has more than climatic implications for forestry. Carbon dioxide is a fundamental component of the photosynthetic reaction from which all wood is derived. A cubic metre of wood contains about 200 kg of carbon, all of which is derived from the atmosphere. It can be safely assumed that the 25% increase in atmospheric CO_2, half of which has occurred since 1950, is already influencing productivity. However, several studies have indicated the opposite of what might be expected, because of the negative impacts of increasing levels of airborne pollutants (McLaughlin et al. 1983).

There is abundant evidence that CO_2 enrichment increases growth under controlled environments, and can be used profitably for that purpose (Tinus 1972). There is also evidence, from agricultural research, that weed species are more responsive than crop species (Patterson and Flint 1980). In view of the opportunistic growth strategies of weed species, we should not really be surprised by this, and can expect the same to occur in forestry, not only with herbaceous weeds, but also with the unwanted fast growing hardwoods. By the same token, certain fast growing trees, such as hybrid poplars (*Populus*), may become increasingly attractive for industrial forestry simply because they are better able to exploit the new conditions.

The direct effects of CO_2 enrichment will be greatest when other factors, notably light, temperature, nutrients, and water, are not limiting. Thus, when the canopy closes, the limitations of light may well reduce the impact of CO_2. The problems inherent in testing this are obvious and illustrate further why predictions of the long-term impacts of CO_2 are tenuous.

Other phenomena of interest to foresters may be associated with higher concentrations of CO_2. These include an increase in the efficiency of water use, resulting from reduced stomatal apertures. The effect has been observed in pine (*Pinus*) species under soil moisture potentials as low as -1500 kPa (Hurt and Wright 1976). It has been suggested by Idso and Brazel (1984) that streamflows in arid regions would be increased as a result of reduced transpiration, rather than be decreased as has been forecast for CO_2-induced changes in climate (Revelle and Waggoner 1983). Another pertinent effect is the stimulation of nitrogen fixation, as observed in certain agricultural species (Hardy and Havelka 1975). Soloman and West (1985) have reviewed a wide range of effects of CO_2 enrichment on forest ecosystems.

The direct effects of CO_2 enrichment are bound to be important. They must be considered as a part of the climate change scenario. They will interact with climatic factors, especially temperature and precipitation. Properly managed, these effects can be positive. And, above all, they are the most reliable of our speculations. CO_2 has increased, and will continue to increase. Only its future rate is uncertain.

Effects of CO_2-Induced Climate Change

The expected rate of increase in CO_2 and other gases, their effect and that of positive feedback from other processes, such as lower albedos, will lead to an estimated increase in mean global temperature of between 1.5 and 4.5°C by the middle of the next century. The effects will be magnified in the north because of large changes in albedos. Since tree growth responds positively to CO_2 enrichment, higher temperatures, longer seasons, etc., it would appear that forest productivity in Canada will increase. In the long run, this is almost certainly true. But, then, we are talking about forests that will have evolved in tune with local conditions. If local conditions change quickly, the existing community is no longer adapted.

Past variations in climate indicate what might happen. Consider, for example, what happened in northern California during several years of unusually severe drought in the 1970s (notably 1975 and 1977). In those years, several species of bark beetle (*Dendroctonus, Ips, Melanophila,* and *Scolytus*), root rot (*Fomes*), and dwarf mistletoe (*Arceuthobium*) invaded large areas of ponderosa pine (*Pinus ponderosa* Laws.) stands (Page 1981). Losses, from the combined effects of drought stress, pests, and diseases, from 2 1/2 million ha of national forests totalled 45 million m^3 over 4 yr - twice the annual production of Ontario.

Bark beetles are notorious pests in Western Canada. In 1983, mountain pine beetles (*D. ponderosae* Hopk.) killed 18 million m^3 in British Columbia — equal to half the production volume of the British Columbia Interior forest industry. Bark beetles are sensitive to climate and thrive in hot dry summers and mild winters. Their requirements have been modeled by Safranyik et al. (1974) to estimate outbreak hazard indices for British Columbia. It may be a concern, therefore, if, as seems likely, the prognosis for climate change in that region is for conditions to become more favorable for the beetle.

These examples remind us that trees do not necessarily thrive in climates that favor them as individuals, but will survive where the checks and balances of biotic and abiotic factors reach a tolerable equilibrium. Almost all of these factors are either affected by climate or are themselves elements of climate. A shift towards warmer, longer seasons may well favor the growth of lodgepole pine, but not its survival, because pests will also respond, perhaps more so, and much faster. The latter point is particularly important. Any species of animal or plant can probably respond more rapidly than trees to environmental change. Furthermore, fire, one of the most important factors affecting forests in Canada, is highly sensitive to climate.

Given our paucity of knowledge of how ecosystems work, of how individual species are affected by climate and CO_2, and of how species and factors interact, it will prove extremely difficult to develop a simulation model of stand response to climate change. It will take many years of investigation to achieve this, even if it is possible, and we may not have the time, and certainly don't have the resources, to do it presently.

An alternative to development of complex simulation models can be found in the establishment of empirical relationships, present or past, between vegetation and climate. Given these, and a map of the projected distribution of climatic parameters used in the relationships, it is possible to generate a map of projected vegetation distribution. The aforementioned example of bark beetle distribution illustrated the first two steps in this process, applied to a single insect. A comprehensive approach to forest ecosystem modeling, in which climate-ecosystem relationships are established to generate hypothetical vegetation maps, is also possible.

Unfortunately, Canadian forest ecosystems generally have not been characterized by climate variables alone, but have embraced soils (Lacate 1969) or observed distribution of forest types (Rowe 1972). An additional problem is that the currently available General Circulation Models do not express climate in biologically meaningful terms, nor on a scale that is practical for regional analysis. Notwithstanding these shortcomings, Emanuel et al. (1985) developed a data base of global climate from over 8000 weather stations, fitted to a half degree global grid. The grid was then transformed into vegetation units, based on the Holdridge (1947) vegetation classification system that incorporates precipitation and temperature. The map generated showed some significant inconsistencies with known vegetation distribution; for example, separate wet and dry boreal forests were distinguished. The scheme did not incorporate any edaphic factors, other than those implicitly associated with current climate. A second map was then generated from estimates of climate under a doubled CO_2 scenario. Some remarkable changes were indicated: tundra and the boreal forest disappeared and there was a massive intrusion of grasslands and cool temperate forest into Canada.

As Soloman and West (1985) point out, this approach is based on a climatic rather than vegetation classification. Many of the zones do not coincide with observed distribution of vegetation because the climate parameters used are not critically important to the distribution of plant types. In view of such difficulties, and the current inherent coarseness of the global model, implications to be drawn for the forest sector can only be of the very broadest nature. It would appear that the biomass of Canadian forests will eventually increase. However, there is no accounting at present for the critical transitional period in which existing forest ecosystems will be subjected to changing climate. Furthermore, it is important to recognize that the doubled CO_2 scenario is an arbitrary point in a protracted sequence of climate change, induced by CO_2 elevations that may attain six or even eight times current concentrations over the next two centuries (Nordhaus and Yohe 1983). Thus, from a practical point of view, the foreseeable future holds disturbance and transition, rather than the realization of a new steady state. Nevertheless, a reliable estimate of what that steady state eventually may be should enable foresters to judge the effects of a transitional period. The empirical model is the only approach currently available that enables us to deal with the climate change issue in a comprehensive manner, and it allows immediate revision when new or improved data or relationships are established. Palaeobotany may provide valuable verification, especially as ice-core samples of ancient atmospheres are now permitting us to determine past levels of CO_2.

Anticipatory Stratagems

The time frame for a $2xCO_2$ scenario is about 70 yr or less. Recently planted trees will be maturing in climatic regions for which they are ill-adapted, if indeed they survive that long. It will take many decades for genetic adjustment, even aided by reforestation programs. Davis (1981) has estimated that forests have migrated 100–400 m/yr during the past 1500 yr, and this was under natural conditions where no man-made environments interrupted the genetic continuity of forest ecosystems. Today we have a very fragmented remnant of natural forest ecosystems south of the Canadian Shield from which genes may migrate. The prospects for renewal are disturbing, the more so when we realize that fire, pests, and disease will respond with climate change and associated climatic variability. Mature forests will be affected most by climate change. The faster change occurs, the less smooth the transition and the greater the disruption for the forest sector.

Bearing in mind the uncertainties surrounding this issue, we must be extremely careful in advocating any silviculture measures to anticipate climate change. One of the safest ways to address the problem is to shorten rotations, so that our commitment to a given climate is lessened. Fortunately, this simply translates into intensive forest management and modified utilization of resources, both of which are already receiving attention. A wise precaution would be to conserve an adequate gene pool at specific and intraspecific levels, from which new forests may evolve. In this respect, it is worth noting that once elevated, CO_2 will take centuries to regain its current level. Other priorities for consideration should include a better understanding of the relationships between forest ecosystems and climate, validation of these relationships through palaeobotanical investigation, and the possibilities for exploiting higher concentrations of CO_2.

In conclusion, attention is drawn to the recently inaugurated International Geosphere-Biosphere Program (IGBP) of the International Council of Scientific Unions. The objective of IGBP is to describe and understand the interactive physical, chemical, and biological processes that regulate the earth system, the environment it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human action. Significant among priority research topics (ICSU 1986) are the design and selection of ecosystem experiments in relation to global change, the role of biological diversity in global change, use of spacecraft for detecting change, and biomass projects to reconstruct the global environment and patterns of vegetation over the past 20 000 and 200 yr. A Canadian response (Royal Society 1986) to IGBP has also suggested priority topics, including changes in the boreal forest environment, and genetic diversity and response to change. It is in the long-term interests of forestry in Canada that foresters follow developments in this program and participate actively wherever appropriate.

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Summary

SESSION III. CLIMATIC APPLICATIONS IN FOREST GROWTH AND DEVELOPMENT

Forest Production

In terms of demonstrating a sensitivity to the relationships between climate and forest production, the presentations at Forest Climate '86 showed that the Canadian forestry community has paid little attention to accelerated forest growth and production. The emphasis appears to have been placed on increasing productivity by reducing forest decline. This emphasis is normally associated with exploitation of the resource (i.e., protect for harvest). To remain economically competitive, Canada must place at least equal emphasis on optimizing productivity. This involves an awareness of the associations between forest productivity, the land, the climatic resources and the use of these concepts in forest management.

Methods such as stand structure alteration, drainage and fertilization are being examined as a means of accelerating or optimizing forest growth and development within existing climate and land resources. Some of the results of these studies have been successfully integrated into forest management practices. In several cases these management options have ramifications on the microclimate and forest growth and development and have been examined to some degree. However, knowledge of the interaction between climate and the effectiveness of these options in terms of the optimization of productivity is limited. In addition, the applicability of the results of these studies is normally restricted to their geographical area of development due to the limited scope of the transfer of the technology and the lack of translation of site-specific study results to the broader scale by using the relationships among the micro-, meso-, and macroscale climates.

Therefore, it is recommended that:

1. relationships between climate and methods of forest productivity acceleration or optimization be given greater emphasis in studies and in particular that the results be capable of being related from small- through large-scale climatologies;
2. stand modification for microclimate alteration be examined for its impact on productivity; and
3. associations between climate and treatment effectiveness be examined for better definition of application windows (e.g., fertilization, spraying).

Forest Depletions

Fire — "Fire danger" refers to an assessment of both fixed and variable factors of the fire environment (i.e., fuels, weather, and topography) that determine the ease of ignition, rate of spread, difficulty of control, and impact of wildland fires. The process of systematically evaluating and integrating the individual and combined factors influencing fire danger is referred to as fire danger rating. Fire danger rating systems produce qualitative and/or numerical indexes of fire potential which are used as a guide in a wide variety of wildfire and prescribed fire management activities. The Canadian Forest Fire Danger Rating (CFFDRS) is the national system of fire danger rating used in Canada. The CFFDRS includes all guides to the evaluation of fire danger and the quantitative prediction of fire behavior such as the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System.

The reliability of the CFFDRS and any computer simulations that depend partly on the CFFDRS are limited largely by the availability of weather data of sufficient quantity, quality, and timeliness to produce reliable estimates of wildland fire potential over long projection periods. In most forested areas of Canada, the present fire weather station network densities are so sparse that the usefulness of the CFFDRS and related applications are severely restricted due to the problems of spatial variability. In addition, the inherent difficulty in providing sufficiently accurate and timely forecasts of the weather parameters required to calculate the values of the various components of the FWI and FBP systems does limit the reliability of the CFFDRS as a means of predicting fire occurrence and behavior to a relatively short-term outlook (i.e., less than 24 h).

Therefore, it is recommended that:

1. the need for updating and improving fire weather station networks (i.e., siting and instrumentation) be examined and that the possibility of multipurpose (i.e., fire and silviculture) weather stations be explored. This process can be relatively simple and inexpensive considering the increasing availability of reasonably priced automated dataloggers;
2. methods be developed to integrate weather information from various sources (e.g., satellite, radar, and lightning locator systems) into the forest fire intelligence system to achieve a better assessment of spatial variability in airmass or weather component of the fire environment; and
3. research be accelerated into assessment of the impact of synoptic-scale climate and weather on the occurrence and behavior of forest fires and that the results of this research be transferred to the operational level.

Insects — Significant achievements have been made in understanding the relationship between the dynamics of some insect populations and climatological factors. These relationships and the defined linkages between weather variables and spraying efficiency have been integrated into operational procedures for defining spray program windows. However, the application of these procedures in operational spray programs is in some cases ineffectual, particularly due to the lack of required meteorological data. In addition, the ability to define a spray window within which the application will be most effective is limited by the lack of knowledge in some cases and by inadequate technological transfer in other cases.

Therefore, it is recommended that:

1. training of involved staff be undertaken to integrate known technological procedures into operational spray programs including the definition of the effective spray window in terms of physiological and weather data relationships including the selection, setting-up, and use of appropriate meteorological observation systems;
2. the current understanding of the relationships between insect population dynamics and climate be expanded through appropriate studies to include all the significant forest insect species and, where the parasites play an integral role in the pest population dynamics, the relationship between climate and parasite populations;
3. the relationship between weather/climate and spray

program effectiveness be defined objectively and the technology transferred to the operational level.

Pollution — Significant contributions have been made to the understanding of long-range transport of air pollutant (LRTAP) concepts and the implications of pollutants to the forest ecosystem. However, many questions remain unanswered regarding the direct linkages between forest productivity, forest health, and pollutants. In most cases the inability to define the impact of pollutants stems from the lack of knowledge of the role the various factors play in determining forest productivity and its variability. The capability to define these factors that directly contribute to productivity and its variability will facilitate the identification and relative contribution of various stress factors, including pollutants.

Therefore, it is recommended that:

1. an integrated effort (climate, soil, and tree physiology) be undertaken to develop a comprehensive simulation of forest productivity using detailed growth layer data; and
2. climate stresses (including airborne pollution) be identified, evaluated, and documented and that this information be recorded annually as forest depletions (or accelerations) in forest management planning and allowable cut models.

Climate Change — It is generally recognized that the concentrations of atmospheric CO_2 and other trace atmospheric gases are increasing. As a result the radiation balance and thus the climate will change, although the magnitude and timing of this change remain highly uncertain. For forestry, the impact of increased atmospheric CO_2 has both a direct biological affect and an indirect effect through climate change. However, it is difficult for the forest manager to consider the implications of a climate change that may occur in the next 50 yr when most managers operate within a 5 to 20-yr planning time frame with greater than 50-yr rotation time frame. The consequences of this management time frame incompatability suggest that climate change and variabilities both in the short-term and long-term should be examined.

Therefore, it is recommended that:

1. the impact of CO_2 on forest systems be examined in the forest environment including the implications regarding water efficiency, biological productivity, and the relationships between crops and weeds;
2. an integrated (climate and physiology) forest productivity model be developed in which climate is the driving factor and various climate scenarios (change and variability) can be examined leading to sensitivity analyses related to productivity;
3. forest systems and regions most susceptible to change when climate is altered be identified. This will supply forest managers, for example, with information directly applicable for species and site selection alternatives and current timber resources.
4. models capable of examining the implications of climate change and variability on forest pests, diseases, and fire be developed.

Taming the Forest Economist

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Abstract

Economics is often seen as a wild and woolly science based on assumptions. The challenge of the policy economist is to replace assumptions with facts, to narrow down the unknowns in the equations. Forest economics is being used increasingly to assess alternative silviculture prescriptions, to priorize sites based on their return on investment, assess the economic accessibility of wood, and for a variety of other purposes. Good growth and yield data, information on susceptibility of stands to disease, insect, and fire losses, and research on treatment effects are critical to these assessments. Scientists play a key role in providing such factual data for economic analysis. The economist, in turn, can be useful to the scientist by providing the framework needed to cost-justify the scientific effort.

Résumé

L'économie est souvent considérée comme une science bizarre et nébuleuse qui s'appuie sur des hypothèses. Le défi que doit relever l'économiste du secteur des politiques est de remplacer les hypothèses par des faits, de déterminer les inconnues dans les équations. On utilise de façon croissante l'économie forestière pour évaluer les prescriptions sylvicoles de rechange, établir la priorité des terrains d'après le rendement des investissements, estimer l'accessibilité économique du bois, ainsi que pour diverses autres fins. Ces évaluations reposent sur des données fiables de croissance et de rendement, une information concernant la vulnérabilité des peuplements à la maladie, aux insectes et aux incendies, ainsi que sur des études de l'impact des traitements. Les chercheurs jouent un rôle clé en fournissant de telles données aux fins de l'analyse économique. En retour, l'économiste peut faciliter la tâche du chercheur en offrant la structure nécessaire pour justifier les coûts de l'effort scientifique.

The era of government constraints has brought with it increasing demands for economic justification of program expenditures. In the area of forestry this has meant an adjustment both for the economist and for the forest scientists and managers. Forest economics in the past tended to be largely an academic domain. Much of the research done in this area had no immediate practical application to field forestry and forest research.

Today, however, the trend is toward applied economics or policy economics. The objective is to use economics to complement the science and practice of forestry.

The shift in emphasis is noticeable in Ontario where field foresters, forest supervisors, and managers are encouraged to incorporate economic analysis in management planning. Forest economics is being used increasingly to assess alternative silviculture prescriptions. At the site level fundamental financial analysis principles are applied to alternative silviculture investments to determine where the highest net present values or equivalent annuities will be achieved. At the management unit, district, and regional levels, information on site, species potential, silviculture costs, and future wood demand are integrated into models designed to priorize sites based on their return on investment. Such models will help us direct our investment in the new forest and meet Forest Production Policy targets in the most efficient way.

As we combine harvesting an existing old forest with cultivation of a new future forest, we recognize the need to integrate optimally harvesting and silviculture decisions. Economic analysis combined with information on site, climate, and soil will help us to identify where to direct the harvesting and regeneration efforts. Both simulation and linear programing models are available to explore alternatives that meet wood supply requirements over an extended period.

The economic accessibility of wood today and in the future is a key concern to policy makers. Although many of Canada's regions have vast supplies of mature timber, operability factors and distance from mills make some of these areas uneconomic to exploit. Changes in utilization and technological improvements in harvesting could improve the economic supply picture. But higher energy and labor costs could have the reverse effect.

Many of our economic analyses depend on assumptions that we make about the future — the demand for wood or different sizes and species, the competing returns from alternative investments, the real value of wood products in the future (itself a function of supply and demand developments here and in other parts of the world).

To the scientist the uncertainty of economic analysis and its heavy reliance on modeling and assumptions compared with the prevailing scientific paradigm of logical empiricism and hypothesis testing may make the economist seem like a strange bedfellow.

But science and economics can be constructive partners in the forestry enterprise. Economic analysis can only proceed and improve with increased knowledge of the underlying biological fundamentals. Good growth and yield data, information on susceptibility of stands to disease, insect, and fire losses, and research on treatment effects are all critical to our assessments of where and how much to invest in the new forest.

At present there are many gaps in our knowledge of the biological response to different site conditions and treatments. The economist has had to deal with these gaps in two ways: (1) by making assumptions based on experience from other jurisdictions and whatever data exist but qualifying the model with probabilities of achieving various results, and (2) by working "backwards," that is fixing the economic criteria that must be met (a target return on investment, for example) and solving the model for the growth and yield response that will be required to meet the economic standard.

Scientists clearly have a dual role to play in this process. In the first instance they are the first line of attack on the biological unknowns. Their work will permit us to narrow down the unknowns and produce models with greater power and credibility. In the second instance the scientist is often in a good position to judge whether or not the economic standard can be met. Even in the absence of hard and fast experimental results, scientific knowledge and experience will enable one to judge whether the required growth and yield responses are within the range of realism.

Clearly forest science has a role to play in assisting the economist. But economics also has a role to play in assisting the scientist. As the title of this paper suggests, the scientist can tame the forest economist and even make good use of some of his tools of the trade. One area in particular where economics can support the scientific effort is that of cost-benefit analysis. Agricultural researchers have been using this technique to support their programs for years. Essentially, the economic analysis looks at the benefits to be derived from a particular innovation in the future, discounts the value of these benefits to the present time period, and compares them with the present value of the costs of the research effort.

The key to this method is determining monetary values. While we tend to think of the benefits of research in biological terms (greater disease resistance, improved growth, shorter establishment time, etc.), all of these effects have financial implications regarding either costs or returns or both. For example, research in tree improvement could save establishment costs (plant less hectares for the same amount of wood), save protection costs (greater insect and disease resistance), increase the present value of returns (by shortened rotations), reduce operating costs at harvest time, and enhance wood quality. All of these results have a dollar value.

Sensitivity analysis, another tool of the economist, can be particularly helpful in directing the scientific effort. With this method the analyst tests the responsiveness (or sensitivity) of the dependent variable (usually NPV or return on investment) to changes in one of the independent variables (yield, rotation age, discounting factor, treatment costs, probability of re-treatment, etc.). If the outcome is very sensitive to changes in a particular variable, this is an area where more time and effort should be spent to gather data. If, however, the model is relatively insensitive to changes in a variable, there is less need for an intensive effort to get more accurate information. The result is a hierarchy of research priorities related to the goal of assuring the best return on investment and a means of justifying the research effort to those who allocate program budgets.

Hand in hand the scientist and economist make a powerful team in the forestry community. Both are engaged in the pursuit of understanding to improve the management process and better employ our resources. Each can gain from taming the energy of the other toward common goals.

Impact of Climate Change and Variability on Wood Quality

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Abstract

This report describes the growth and average wood density distribution in the stem-wood of white spruce (*Picea glauca* (Moench) Voss) in Alberta; Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) in British Columbia; and coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on Vancouver Island. Six white spruce trees were sampled at four locations on a south to north transect in Alberta. Intensive sampling and X-ray densitometric data acquisition were used for mapping average ring density distribution in the stem-wood. Weighted average stem-wood density declined from south to north, over a distance of 730 km, from 0.43 to 0.39 g/cm³. Five Interior Douglas-fir trees were sampled at each of two locations in south-central British Columbia, about 100 km apart — a "continental wet" and a "continental dry" location. Within-tree average ring density variation was, due to juvenile-mature wood difference, 10% and 30% for the wet-belt and dry-belt locations. Weighted average stem-wood density was 0.43 and 0.47 g/cm³ for the wet- and dry-belt Douglas-fir, respectively. The impact of short-term climate variability was assessed on 10 coastal Douglas-fir trees' yearly ring-density cross-dating patterns. Current research efforts deal with estimating tree growth from climate data using response function equations.

Résumé

Ce rapport décrit la croissance et la répartition de la densité moyenne des cernes dans le bois de fût de l'épinette blanche (*Picea glauca* (Moench) Voss) en Alberta; du douglas bleu (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) en Colombie-Britannique; et du douglas taxifolié (*Pseudotsuga menziesii* (Mirb.) Franco) sur l'île de Vancouver. On a échantillonné six épinettes blanches, à quatre endroits, sur un transect sud-nord en Alberta. Les données d'un échantillonnage intensif et d'études de dendrométrie aux rayons X ont servi à cartographier la répartition de la densité moyenne des cernes dans le bois de fût. On a constaté que la densité moyenne pondérée dans le bois de fût diminuait de 0,43 à 0,39 g/cm³ du sud au nord sur une distance de 730 km. On a échantillonné cinq douglas bleus à deux emplacements du centre-sud de la Colombie-Britannique, distants d'environ 100 km, l'un dans une zone de «climat continental humide» et l'autre dans une zone de «climat continental sec». On a attribué aux différences entre le bois juvénile et exploitable une variation de densité moyenne des cernes dans les arbres de 10 % pour la zone humide et de 30 % pour la zone sèche. Des densités moyennes pondérées du bois de fût de 0,43 et 0,47 g/cm³ ont été obtenues respectivement pour les douglas bleus du climat humide et du climat sec. On a étudié l'impact de la variabilité climatique à court terme sur les configurations de densité annuelle de cernes avec croisement de dates, dans 10 douglas taxifoliés. Les travaux actuels de recherche portent sur l'estimation de la croissance des arbres à l'aide de données climatiques et d'équations de fonctions de réaction.

Introduction

The purpose of this paper is to provide some concrete examples of the potential impact of climatic change and variability on wood quality. The effect of climatic change and climate variability will be inferred from wood quality characteristics of two species grown under different climatic regimes in Western Canada.

Wood quality is a measure of the wood characteristics that influence the properties of products made from wood. Density is the single most important descriptor of clear wood quality. It is the primary determinant of clear wood strength and yield of pulp per unit wood volume. It is also related to heat per unit volume produced during combustion, shrinkage, and swelling, heat transmission, machining, and other properties. Unfortunately, density is very difficult to measure on a small scale (like individual annual rings) by conventional methods. Therefore, ring-density data were measured by X-ray densitometry.

Research has demonstrated the strong influence of climatic variations on tree growth both in short-term (annual) variation and long-term (decades, centuries) changes (Fritts 1976).

Recent studies of long-term climatic trends for the Boreal Forest Region of Western Canada have identified statistically significant increasing temperature and precipitation trends for the predominantly forest subregion (Singh and Powell 1986).

Lately, there is an increasing concern in Canada about the probability of significant climate change due to rising concentrations of carbon dioxide in the atmosphere (the "greenhouse effect"). Most climatic change predictions suggest a warming trend which could prove either disastrous or highly beneficial, depending on moisture availability and other factors. For example, the boreal forest currently occupies a zone with a summer temperature range of only 2°C. A long-term temperature increase may significantly alter the northern and southern limits of tree growth, as well as affecting the quality of wood produced (Powell 1981).

Forest land management and planning precepts need to be evaluated with respect to recent findings of atmospheric research, and climatic change considered as a factor in forest planning and ecological impacts.

This paper shows relative density distribution differences, attributable to climatic differences, in the stem-wood of white spruce and Douglas-fir. These examples are taken from past research projects at Forintek, dealing with biomass productivity and wood quality.

Principles of Tree Growth and Wood Anatomy

Because wood quality will be discussed in terms of density, it would be helpful to review some of the basic concepts and definitions of tree growth and wood anatomy. An understanding of this general pattern, and the major physiological forces driving it, is a big step towards the practical application of density data in the utilization of wood and fiber.

Although the crown of a tree is both the source of nutrients and the regulating center of wood production, wood is not produced directly by photosynthesis. Rather, wood results from successive divisions of the vascular cambium, using energy derived form the products of photosynthesis. After cambial division each successive cell (fiber) undergoes enlargement, wall thickening (differentiation), and lignification (maturation). The rate of cell division and final size are both thought to be largely under the influence of growth-regulating hormones (auxins).

Active growing season (cambial division) begins at the time of flushing. At this time, usually in mid-May to mid-June in Canada, buds break their scales and reveal their green needles. Low density earlywood (0.2–0.3) is produced from this time until about mid-July, when the cessation of height (leader) growth and new needle maturity takes place (Kennedy 1970).

About mid-July the new foliage ceases to be a net sink of photosynthate and becomes an exporter; more material becomes available for wall thickening. Also, the reduced crown activity limits auxin production, which helps trigger high density latewood (0.7–1.0) formation. Thus, the active growing season lasts about 4 mo until about mid-September, when the lower temperatures and the reduced photoperiod bring on tree dormancy.

In summary, the growing tree forms large, thin-walled fibers in the early part of the growing season (earlywood), and small thick-walled fibers during the latter part (latewood). Collectively, these fibers form an annual ring. Radial growth begins first near the top of the tree and proceeds gradually downward in the stem, resulting in more earlywood and wider rings in the upper crown region (near the pith). Transition to latewood occurs first near the base, farthest from the source of auxin supply, and proceeds upwards. Therefore, the density of an individual fiber is thus determined by its relative position, its distance from the active live crown region, and the time (season) of its formation (Larson 1969, Megraw 1985).

The relative density of most commercially important Canadian softwoods ranges from about 0.2 in the earlywood to about 1.0 in the latewood. The average relative density of the different softwood species ranges from about 0.3 (western red cedar) to 0.55 (Douglas-fir and western larch), largely dictated by the proportion of the low density earlywood and high density latewood in the annual rings. The width and density of annual rings are important indicators of changes in climate and reflect these from one degree to another. Modern dendrochronology and dendroclimatology are founded on this principle.

Biological, Genetic, and Climatic Content in Trees and Tree Rings

Wood produced by trees of the same species is often thought to be identical in all structural and physical characteristics. In reality, different pieces of wood even from the same tree are never identical and are similar only within broad limits. Dimensional and physical characteristics (such as ring width, percent latewood width, relative density, fiber length, etc.) within trees are variable and they exhibit a range of values. The variations that are present can be related to radial (pith to bark) or axial (base to top of stem) position of the sample within an individual growth layer within the tree.

Dimensional and physical variables in wood (or individual tree rings) are influenced by the following factors: (1) changes in the cambium as it ages (biologic); (2) genetic controls that govern the form and growth of the tree; and (3) environmental influences, such as climate, geology, and nutrient supply.

Because of the interaction of these influences, sometimes it is very difficult to ascribe variability in tree rings to a single factor or even to a combination of factors affecting tree growth (Panshin and de Zeeuw 1980).

Previous work at Forintek documented within-tree variability of relative density in five commercially important tree species in British Columbia (Jozsa and Kellogg 1986). The relevant parts of this paper will be discussed in synoptic terms below.

Materials and Methods

SITE SELECTION AND SAMPLING OF WHITE SPRUCE

Two north–south transects, with eight sampling sites, were set up through the boreal forest. The Alberta transect, close to 115°W longitude, extends from the Peace River area in the north to near the southern limit of the boreal forest in Alberta. The Manitoba transect, close to 100°W longitude nearly traverses the boreal forest. Sampling sites are shown in Figure 1.

An attempt was made to sample even-aged 110-yr-old white spruce stands with no evidence of past human influence or damage from insects or pathogens. All sites were also on well-drained, level terrain in mature closed-canopy stands.

For estimating forest biomass production six trees were felled, delimbed, measured, and sectioned at each location. Seven cross-sectional disks were cut from each tree; one at the base, one at breast height, and five others at equal intervals along the stem. These disks provided information about ring width, ring density, taper along the bole, and average yearly height increments between sampling points for detailed stem-wood analysis. Two average-radii sub-

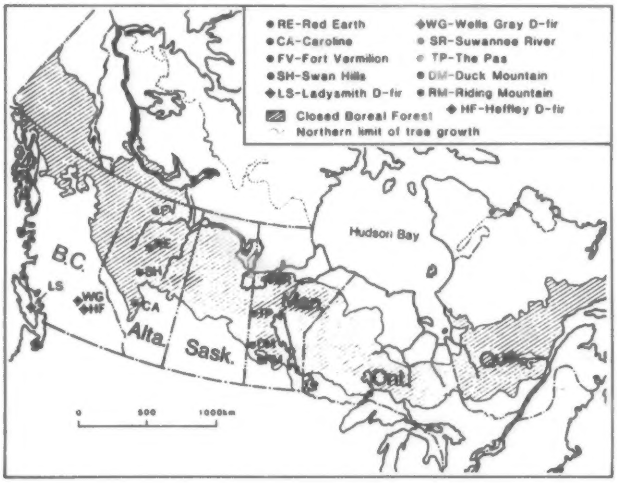

FIG. 1. Sampling sites.

samples were cut from each disk for tree-ring analysis (for further sampling detail see Jozsa et al. 1984).

Site Selection and Sampling of Douglas-Fir

A decision was made to sample Douglas-fir stands that were about 50 yr old. This age was thought to approximate harvest age of intensively managed stands. Because intensively managed stands of this age do not exist for Douglas-fir in British Columbia, natural stands were selected on good sites where low stocking densities permitted high wood productivity rates.

For Interior Douglas-fir, five trees were sampled at Heffley, with continental dry climate, and at Wells Gray, with continental wet climate (further sampling detail is described by Jozsa and Kellogg 1986). For coastal Douglas-fir 10 trees were sampled at Ladysmith as part of Forintek's Douglas-fir Task Force (Kellogg 1986).

Five cross-sectional disks were cut from each tree; one at breast height and four others at one-fifth intervals of total height. From these disks two average radii subsamples were cut for X-ray densitometric analysis.

Sample Preparation and X-Ray Densitometry

Ring width and ring density were derived from the average-radii subsamples by computerized X-ray densitometry as described by Parker et al. 1980. Briefly, this consisted of the following steps:

Samples were cut to uniform thickness on a twin-blade saw; surfaced samples were placed on X-ray film with calibration wedges, then exposed at the proper angle by X-radiation; X-ray film was developed and calendar-year dates and other information were marked on it; radiographs were then scanned on a densitometer that provided ring width (resolution 0.01 mm) and ring density data; and data were stored on magnetic tape for further processing.

Tree-Ring Data

The systematic comparison of ring patterns (cross-dating) permitted absolute dating of each annual ring as to the calendar year when it was formed. The success of the procedure depended on well-defined annual rings which varied in width and density from year to year as a result of annual variation of some dominant factors such as precipitation and temperature (climate).

The climatic factor may not be limiting tree growth in most years, but will be controlling annual ring formation in a sufficient number of years to provide a common pattern of marker years. White spruce and Douglas-fir marker years usually are narrow rings with low-density latewood bands. As a rule, radial growth response to climate during unfavorable years is more consistent from tree to tree than it is during years of favorable climatic conditions.

Relative density values were recorded on an ovendry volume and weight basis. The quoted numbers are, therefore, about 10% higher at the 0.45 level than the conventional basic wood density, which is always expressed on a green volume and ovendry weight basis.

The Tree Ring Input Program (TRIP) (Parker et al. 1980) was used to obtain ring-width and ring-density data. Yearly ring width and maximum ring density index chronologies were derived for the Manitoba white spruce locations using a technique described by Parker et al. 1981.

Mapping Relative Density Distribution in the Stem-Wood

Reconstructing past growth and development of a tree by measuring annual rings pith to bark at several points along the bole (i.e. a complete stem analysis) has many applications in forestry. In this paper relative density distribution patterns were compared in the stem-wood from pith to bark, and from base to top.

For white spruce north to south locations were compared, and for Douglas-fir wet and dry climatic zones were examined. For both species three arbitrary relative density zones were delineated and mapped: (1) average range for the species (0.40–0.45 for white spruce and 0.46–0.49 for Douglas-fir); (2) below average (<0.40 for white spruce and <0.46 for Douglas-fir); and (3) above average (>0.45 for white spruce and >0.49 for Douglas-fir).

Density contour lines were drawn with the aid of pith-to-bark yearly average density plots for each sampling height (seven for white spruce and five for Douglas-fir).

Average stem-wood profiles were drawn to scale, representing tree height, stem diameter, and taper. The three density zones were superimposed on these profiles depicting pith-to-bark trends at the various sampling points along the bole.

Results

Average Density Trends in the Stem-Wood of White Spruce from Alberta

Pith-to-bark average ring-density values were summarized for all seven sampling heights for Caroline (southernmost site), Swan Hills, Red Earth, and Fort Vermilion (750 km north of Caroline). The trees were about 110 yr old, 35–40 cm DBH, and 24–28 m tall at the four sites.

The three arbitrary density zones mapped for Caroline, Swan Hills, Red Earth, and Fort Vermilion are shown in Figure 2. Density trends are evident from the base to the top of the stem-wood, from site to site, and from south to north. For example, the density increase from base to top can be seen and understood readily in Figure 2. The gradual "expansion" of the low density (<0.40) wood is evident from south (Caroline) to north (Fort Vermilion). To a lesser degree this expansion is combined with a decline in the extent of the high density (>0.45) core wood. The weighted average stem-wood relative density declines by about 10%

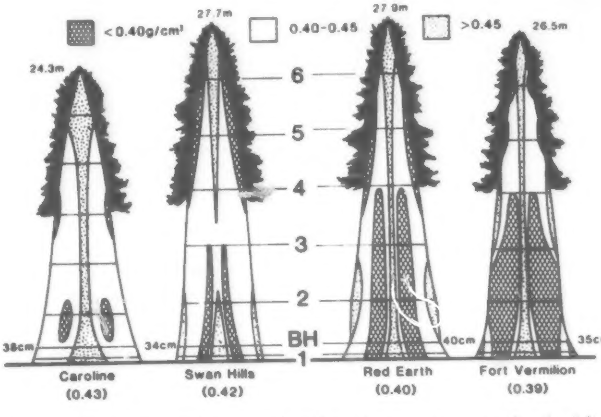

FIG. 2. Relative density distribution in the stem-wood of white spruce from Alberta.

from south to north: Caroline, 0.43; Swan Hills, 0.42; Red Earth, 0.40; and Fort Vermilion, 0.39.

Decreased densities from south to north were attributed to declining latewood content and earlywood densities in the stem-wood because of climate differences.

CROSS-DATING QUALITY OF WHITE SPRUCE FROM MANITOBA

The ring width and maximum ring density site summary chronologies for Riding Mountain, Duck Mountain, The Pas, and Suwannee River are shown in Figure 3. Numerous common marker rings are evident in both ring-width and maximum ring-density chronologies. This is indicative of common climatic signals, as recorded in the trees' radial growth, as far as 650 km apart. Also, strong cross-dating between randomly selected individual cores and site summary chronologies are further proof of strong climatic signals, as shown in Table 1 for Manitoba transect white spruce sites.

Good quality cross-dating of ring width and maximum ring density from site-to-site permitted the construction of an overall Manitoba summary as shown in Figure 3. On closer examination of the individual chronologies, certain synchronous and nonsynchronous marker years emerge. For example, one of the stronger marker years is 1907: both ring width and maximum ring density values are well below the average index value. On the other hand, in 1965 wide rings (peaks) contained low maximum ring densities (valleys). The small black triangles in Figure 3 show several of these examples.

Cross correlations of monthly climate (temperature and precipitation) variables with tree-ring variables were examined to see whether the Manitoba climate signal could be identified. In general, linear correlations were low and no marked differences in correlation values were seen between the northern and southern sites. The degree of correlation of a tree-ring parameter is generally greater with temperature than with precipitation.

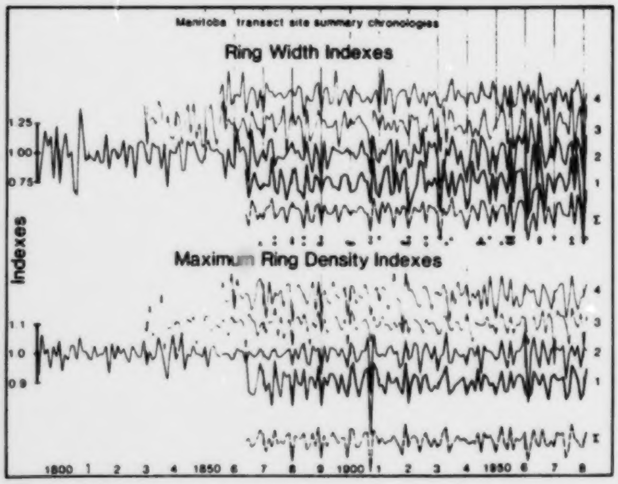

FIG. 3. White spruce site summary chronologies for Riding Mountain(1), Duck Mountain(2), The Pas(3), and Suwannee River(4). An overall Manitoba summary is also shown(Σ).

TABLE 1. Manitoba transect individual core and site summary chronology correlations for 100-yr common time periods.

	Ring width (r)	Maximum ring density (r)
Riding Mountain	0.82	0.80
Duck Mountain	0.74	0.76
The Pas	0.73	0.69
Suwannee River	0.65	0.86

Although no clear-cut patterns emerged from linear correlations with climate it was demonstrated that a strong common climatic signal is contained in these tree rings (Jozsa et al. 1984).

SYNOPSIS OF EXPLORATORY WORK

Previous work at Forintek examined wood quality in five commercially important tree species in British Columbia (Jozsa and Kellogg 1986). The species were Douglas-fir (both coastal and Interior forms), western hemlock, lodgepole pine, Interior spruce (white or Engelmann), and western red cedar. Five trees were sampled intensively at each site, at breast height and at one-fifth intervals of total height. Average yearly ring density trends were examined by X-ray densitometry from pith to bark at each sampling height. Within-ring density variation was the greatest, with three- to fourfold differences in magnitude, between earlywood and latewood. These differences are believed to be largely due to the combination of two factors: biological and climatic. Biologic changes at the cessation of height growth initiated latewood formation which was triggered by the changing climate. Climate also had an impact on earlywood–latewood content and density.

Within-tree average ring density variation was about 10–40% due to juvenile–mature wood differences. Juvenile wood was produced by the trees when the cambium was young in age (about 15 yr). In other words this is an age-related biological phenomenon. In coastal Douglas-fir (and western hemlock) low density juvenile wood was observed for the first 15–20 yr of growth. Then a rapid increase was evident to about age 30, followed by a stable or slightly increasing density trend.

Between-tree variation of cumulative stem-wood density was about 20–30% for the five species examined. This is believed to be the genetic component because the density ranking of trees remained stable during their lifespan. In fact, trees could be ranked reliably according to relative density by about age 15 at each site for the five species.

In addition to yearly development of stem-wood density, growth layer weight patterns were examined also, from age one to sampling age (35–105 yr). The coastal sites were more vigorous biomass producers (as expressed by growth layer weights in the stem-wood) than the Interior sites. In this case, the fundamental site-to-site differences may be related to the temperature regime and the length of the growing season differences between the coast and the Interior of British Columbia. On the coast, trees photosynthesize almost year round, whereas in the continental climate of the Interior, trees are truly dormant (temperatures are below the freezing point) during the winter months. During the dormant season for trees in the Pacific northwest (coast), substantial net photosynthesis occurs over a wide range of environments. Winter temperatures are mild and subfreezing day temperatures are uncommon, even in mountain environments. This is true of soil as well as air temperatures. Frozen soils are extremely rare, even in subalpine environments, thus water uptake is not a major problem (Waring and Franklin 1979). The density differences between coastal and Interior Douglas-fir could be explained by these considerations, which directly affect the net photosynthates produced by the trees.

These density results and discussions must be considered exploratory. Each site was represented by only five sample trees; however, the trends from pith to bark and the rankings (low to high density) were always consistent at each site.

PITH-TO-BARK AND BASE-TO-TOP DENSITY TRENDS IN THE STEM-WOOD OF DOUGLAS-FIR

Figure 4 shows the average annual ring density trends at five sampling heights for a dry Interior (Heffley) and a wet Interior (Wells Gray) Douglas-fir site. The average density range for the species is shown for reference, indicated by cross-hatching from 0.46 to 0.49 (bracketed $\overline{X}$). At Heffley the ring-density trend lines indicate that collectively the first 15 yr of growth (small arrow) at each sampling height are only about 2% less dense than the entire stem-wood (shown by bold black arrow); 0.46 compared with 0.47. It also appears that if there is low density core-wood it is not immediately adjacent to the pith but it is formed, on the average, from age 10 to 20 (note the dip in the trend line of each sampling height in Figure 4A).

The Interior wet-belt Douglas-fir site at Wells Gray produced the most surprising density trends. There are three fundamentally different features noteworthy for this site in relation to the dry-belt site: (1) relatively high density core-wood; (2) very stable density trends at each sampling height from about the 10th ring to bark; (3) relatively low "hemlock-like" total stem-wood density at 0.43. In fact, except for the first 2-7 yr of growth (at each sampling height), the entire stem-wood can be classified as less dense than 0.46.

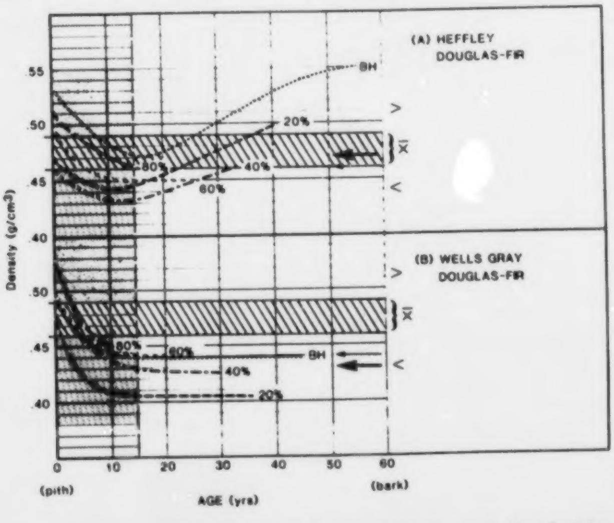

FIG. 4. Average annual ring density trends at five sampling heights for two Interior Douglas-fir sites, (A) Heffley and (B) Wells Gray.

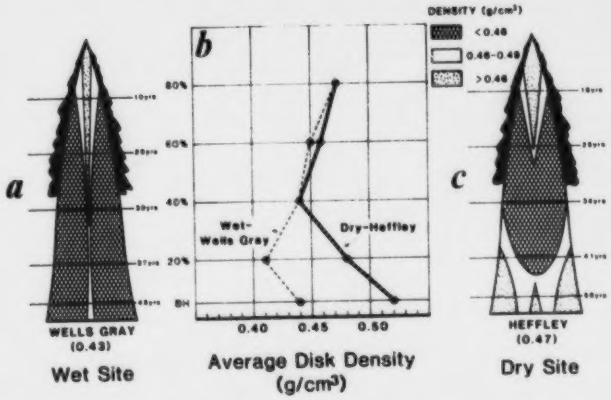

FIG. 5. Density distribution in the stem-wood for wet- and dry-site Douglas-fir showing comparatively low, average, and high density wood (a and c) and average disk densities (b).

Figure 5 shows the relative density distribution in the stem-wood and average disk-density values at five sampling heights for these two sites in British Columbia. The stem-wood longitudinal sections were drawn at the same scale to facilitate site-to-site comparisons. Total stem-wood density values are shown below the site names (bracketed) and the number of annual rings at each sampling height are indicated.

A remarkable similarity can be seen in the top halves of the stems and in average disk density (at 40, 60, and 80% heights). At BH and 20% sampling heights, however, the Heffley trees are about 15% more dense. These differences between the wet and dry Interior sites are thought to be climate related. This type of density mapping, as shown in Figure 5, could prove very useful for studying the results of silviculture treatments and for allocating the raw wood supply to specific end uses. Examples of this would be in pruning (either to "lift" the crown or to keep it low), pulping (more dense wood yields more solid fiber), and engineering applications (greater density means greater strength).

YEARLY AVERAGE RING DENSITY IN COASTAL DOUGLAS-FIR AT LADYSMITH

Figure 6 shows yearly average ring-density values at breast height for 10 sample trees from 1945 to 1984. This represents the last 40 yr of growth for these 50-yr-old trees, showing good cross-dating. Marker rings are evident as follows: relatively low density in 1958, 1967, 1977, 1981, and 1984; relatively high density in 1956, 1957, 1959, 1966, 1968, 1969, 1975, 1982, and 1983.

The average yearly ring density of these 10 trees is shown in Figure 6b. Here the shaded area delineates the range of "peaks" and "valleys" which is the result of year-to-year short-term climatic variability. This climate variability component shows about a 20% range on the average in relative density (0.1 density unit). For 5-yr, 1970–1974, there is very little variation in the average ring-density values, which is followed by much variation from 1975 to 1984. On examination of summer temperature and precipitation, records show similar trends; that is, little year-to-year variability from 1970 to 1974, followed by much variation

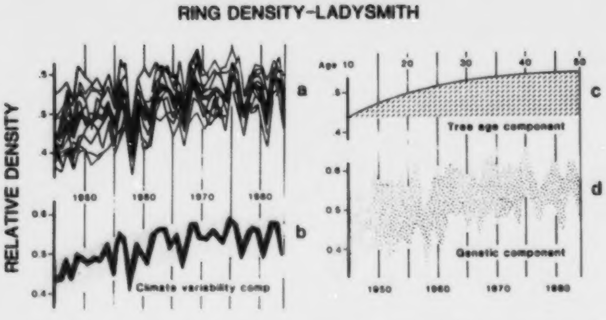

FIG. 6. Plot of yearly ring-density values of 10 Douglas-fir trees from Ladysmith (a); site average climate variability component (b); site average tree-age (biologic) component (c); and the genetic component (d).

from 1975 to 1984. The implications are that if there were no year-to-year climatic variability, this average trend line would be a smooth line (similar to 6c).

The biological tree-age component is shown in Figure 6c. Douglas-fir trees at this site exhibited a similar age-related density trend as discussed under the previous heading. Specifically, from 1945 to 1959 (at years of growth from age 10 to 25) ring density increased from about 0.44 to 0.51 (0.07 density units, about 14%). In the last 15 yr of growth, however, (from age 36 to 50: 1970 to 1984) density increased from 0.535 to 0.550 (0.015 density units, about 3% only). Relative ring density had stabilized as a function of age. For the entire interval, from 1945 to 1984, density increased about 22% (from 0.44 to 0.55).

The area depicted in Figure 6d shows the range between the least and most dense trees, on the average about 0.15 density units or 29%. Because these 10 sample trees occupied the same social position in the forest (all dominant or codominant class) and their rankings were stable through time, this density range is believed to be due mainly to the genetic predisposition.

Conclusions

Many independent climatic studies have shown that our current climate is not the same as it was 100 or 200 yr ago. In addition to "natural" long-term variation (and change), there are increasing man-made influences because of the "greenhouse" effect; scientists predict various scenarios of wholesale environmental change in the near future. Thus, accurate short-term predictions of growth and yield must include the response of trees to climate variations, and the modeling of long-term growth and yield should investigate scenarios with greatly altered mean climate conditions.

It was shown that the width and density of tree rings can provide information about the biologic, genetic, and climatic history of trees to one degree or another. Therefore, the yields of our forest, the amount of wood grown by each tree, and wood quality are tied inseparably to natural forces. The best silviculture and management practices can only enhance the forest that nature creates; they cannot erase or replace the effects of climate. Comparative inferences can be made about the resource of the future by studying past resource development trends and their dependence on climate.

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Effects of Climatic Factors on the Formation of Wood and Its Quality

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Abstract

Wood quality between and within trees of a species varies in response to three principal factors: (a) changes in the vascular cambium with age, (b) genetic potential within a tree, and (c) environmental influences on growth. Climatic factors of the environment influence wood formation both directly and indirectly. This influence is usually exerted during the active period of tree growth and wood formation. Wood quality features known to be affected by climatic factors include wood density, growth rate, proportion of earlywood/latewood, and cell dimensions. Sudden and extreme changes in climatic factors may also leave a permanent imprint on xylem anatomy. The occurrence of drought and frost rings are examples.

Results of laboratory experiments and field observations are presented on the effects of photoperiod, drought, and temperatures on wood formation in larch and hybrid poplar as typical examples.

The results fitted the theory of limiting factors, that is, a factor that falls below an optimal range will set the pace for physiological processes that determine the differentiation and maturation of wood cells.

Résumé

La qualité du bois dans les arbres d'une espèce et d'un individu à l'autre varie en fonction de trois facteurs principaux: l'évolution du cambium vasculaire avec l'âge, le potentiel génétique d'un arbre et les effets environnementaux sur la croissance. Les facteurs climatiques du milieu ont des effets directs et indirects sur la formation du bois. Cette influence est habituellement exercée au cours de la période active de croissance d'un arbre et de formation du bois. Les caractéristiques du bois, qui peuvent être modifiées par les facteurs climatiques, comprennent la densité, le taux de croissance, la proportion de bois initial par rapport au bois final et les dimensions des cellules. Des changements climatiques subits et extrêmes peuvent aussi avoir un effet permanent sur l'anatomie du xylème, comme l'illustrent les cernes de sécheresse et de gelée.

On présente les résultats d'essais en laboratoire et d'observations sur le terrain axés sur les effets de la photopériode, de la sécheresse et des températures sur la formation du bois chez le mélèze et le peuplier hybride qui représentent des exemples types.

Les résultats ont confirmé la théorie des facteurs limitants, selon laquelle un facteur, qui demeure inférieur à une gamme optimale, règle le déroulement des processus physiologiques qui déterminent la différentiation et la maturation des cellules du bois.

Introduction

Wood quality refers to the integration of those physical, chemical, and anatomical attributes that affect the suitability of wood for various products and/or uses. The concept of wood quality is an evolving one and subject to a wide range of interpretations. For construction applications (i.e., "solid wood products"), wood quality may be defined in terms of strength, hardness, freedom from defects, machinability, etc. For pulp and paper products, fiber geometry, ultrastructure, and chemical composition may be more useful.

Wood quality between and within trees of a species varies in response to three principal factors: (a) change in the vascular cambium with age, (b) genetic potential within a tree, and (c) environmental influences on growth. Climatic factors of the environment influence wood formation both directly and indirectly. This influence is usually exerted during the active period of tree growth and wood formation. Wood quality features known to be affected by climatic factors include wood density, ring width, proportion of earlywood/latewood, and cell dimensions. Sudden and extreme changes in climatic factors may also leave a permanent imprint on xylem anatomy. The occurrence of drought and frost rings are examples.

Wood quality and its variation are important concerns to both forest managers and wood users. The manager needs to know whether and how wood quality may be influenced during the phase of crop production. The wood user may need to adjust his process and modify the use to suit quality, or he may develop "specifications" for wood quality in future timber crops.

Within limits, some influence may be exerted on wood quality in future crops by manipulating certain environmental factors. For example, the negative impact of water stress may be prevented or reduced by irrigation. Essential nutrients may be supplemented by fertilization. Silviculture treatment of a forest stand may beneficially alter competition for light and soil moisture. Therefore, an understanding of basic relationships between climatic factors and tree growth/wood formation is important to both forest management and wood utilization.

The purpose of this paper is to review briefly the wood formation/ climatic factor relationships, and to report the results of some laboratory experiments and field observations related to the topic.

Background

Wood formation is a complex growth process. It is the sum total of a series of physiological and biochemical processes, the result of which is a measurable increase in the volume and mass of xylem tissue in trees. While the vascular cambium is the "factory" or "engine" of wood formation, a host of internal and external factors (conditions)

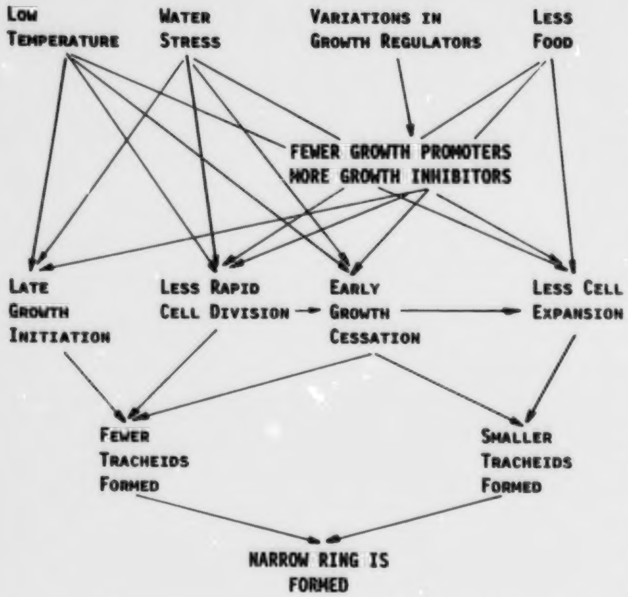


FIG. 1. Interrelationship among factors that influence the processes of wood formation (Fritts 1976).

play a crucial role in both the qualitative and quantitative aspects of the process. Some of the most important internal factors are available food reserves, minerals, water balance, growth regulators, and interactions among various organs. The external (environmental) factors affecting wood formation include light, temperature, water, soil minerals, carbon dioxide, oxygen and others. The individual and combined influence of internal and external factors represent a complex system of interactions. Consequently, it is very difficult to "model" and adequately explain the "climatic factors vs. wood formation" relationships.

One of the most comprehensive discussions of climate vs. tree growth was presented by Fritts (1976). He stated that an understanding of tree growth and wood structure is essential for constructing realistic models relating environmental factors to ring widths or other anatomical features of wood.

The vascular cambium plays a crucial role in the relationship of climate vs. wood formation. Wilson (1964), as well as other authors, viewed the cambium as a type of "biofactory." The factory receives building materials (i.e., organic precursors), energy, hormones, water, and mineral nutrients from the phloem and xylem. The supply of these key ingredients strongly influences wood formation. The influence is usually manifested according to the concept of limiting factors, that is, a factor that falls below an optimal range will set the pace for growth. Fritts (1976) described a model that recognized four primary limiting conditions (factors), and they were (a) temperature of the growing tissues, (b) water stress, (c) growth regulators, and (d) food and mineral nutrients. A schematic outline of such a model is presented in Figure 1.

Temperature influences growth primarily by impacting on respiration and assimilation processes. Kramer and Kozlowski (1960) noted that temperature affects enzyme activity, rate of cell division, and translocation. It also affects transpiration, and, therefore, the internal water balance of cells.

An interesting temperature–tree growth relationship was reported by Mikola (1962) for trees growing at northern latitudes. In northern Finland, radial growth largely depended on temperature. High latewood percentages were associated with longer growing seasons. The amount of latewood was also positively correlated with July temperatures. Mikola found that in current biomass production of Scots pine, the temperature of the previous summer was the most important factor. Needle length, on the other hand, was primarily influenced by prevailing temperatures during their actual growth.

At the cellular level, Richardson and Dinwoodie (1960) studied the effect of temperature on tracheid size and wood density in conifers. They found an inverse relationship between cell wall thickness and night temperatures. Tracheid length and lumen diameter, on the other hand, increased with increasing temperatures, either day or night. These investigators suggested that cell wall thickening was a function of net assimilation rate, which apparently decreased with increasing night temperatures. For *Pinus taeda,* Van Buijtenen (1958) reported that increasing temperatures were associated with a decrease in cell wall thickness without influencing cell diameter. Richardson (1964), on the other hand, found that increased night temperatures favored increased lumen diameters in *Picea sitchensis* and *Pinus radiata*.

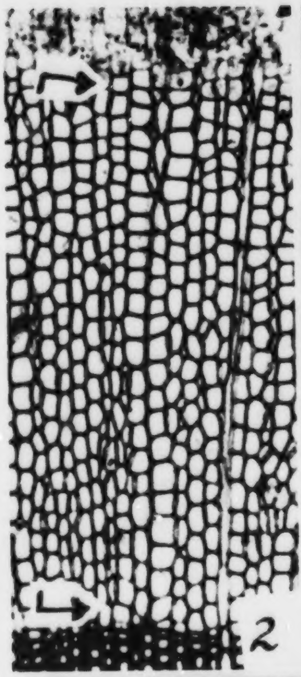
Extreme cold temperatures during the active period of growth can induce the development of frost rings.

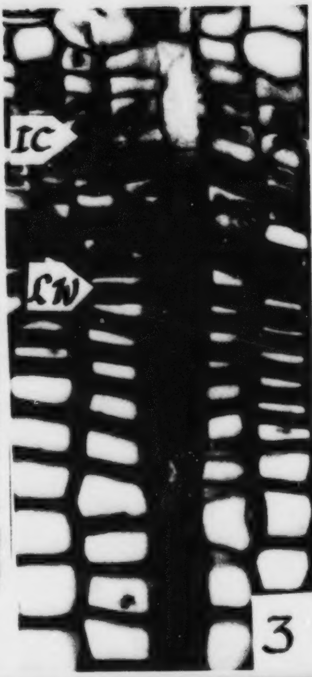
Water stress affects both the quantitative and qualitative aspects of tree growth and wood formation (Zahner 1963, 1968; Kramer 1964). By its direct action, water stress might reduce cell division and cell enlargement. Indirectly, water stress can reduce photosynthesis, auxin synthesis, and the translocation of carbohydrates and auxins to the cambium. Zahner (1968) and Kramer (1964) emphasized that both the direct and indirect effects of water deficits were important in xylem development and cambial activity. The water balance of differentiating cambial cells influenced not only their enlargement but also their metabolism. Water deficits reduced photosynthesis, and thereby the supply of carbohydrates.

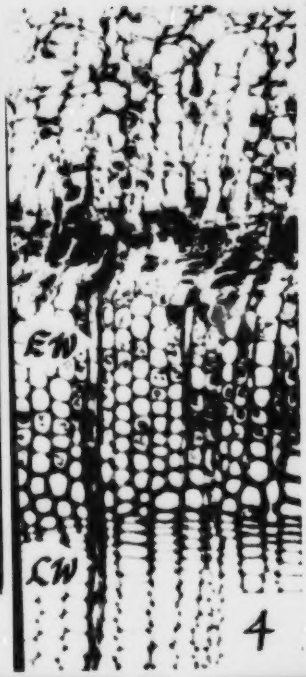
Kennedy and Farrar (1965) observed that drought treatment also influenced lignification in addition to the processes of cell development mentioned earlier. Drought-reduced lignification of tracheids formed on the lower side of tilted jack pine seedlings, which under normal watering would have developed into excessively lignified compression wood cells.

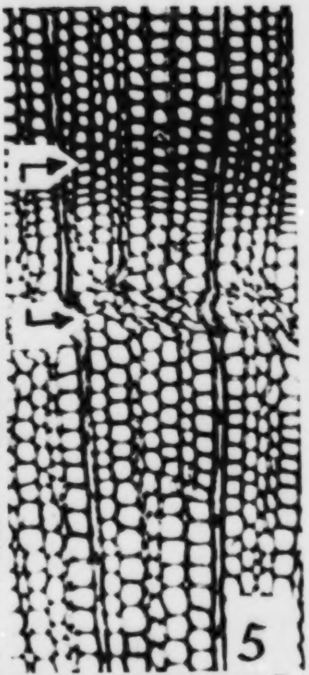
Food and mineral nutrients have a strong and direct effect on wood formation. Photosynthetically produced carbohydrates are the ultimate source of both energy and raw material for tree growth. Trees convert approximately 30 to 50% of their photosynthate into wood (Kramer and Kozlowski 1960). The availability of mineral nutrients cannot be easily linked to any particular climatic factor. However, mineral nutrients can become limiting factors in tree growth and wood formation.

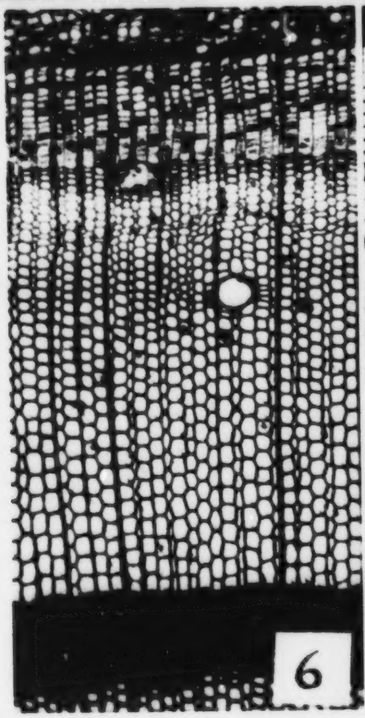
Growth regulators influence not only the amount of apical and radial growth in trees, but also the form, structure, and distribution of developing tissues (Larson 1960,

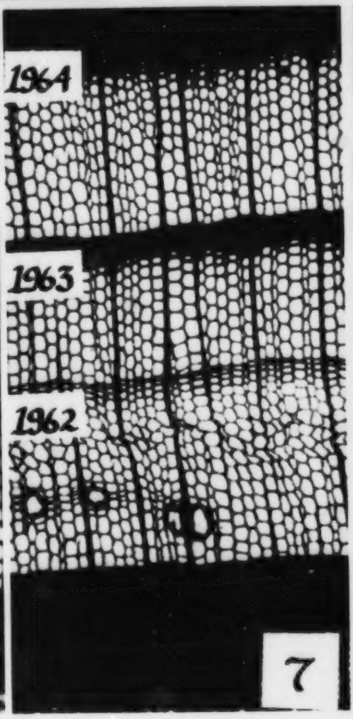


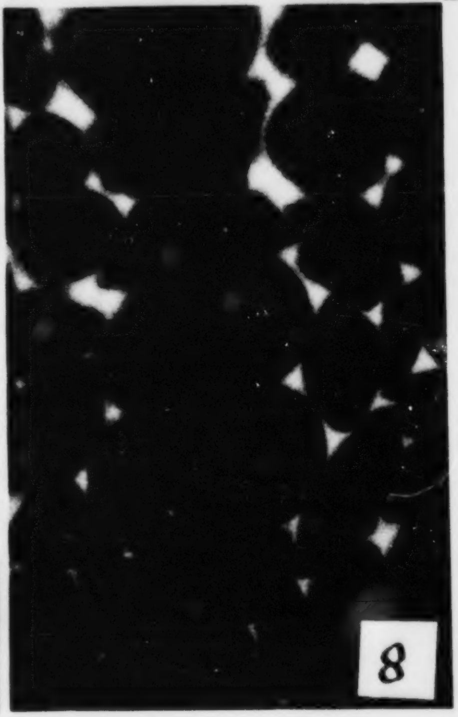












FIGURES 2–8

FIG. 2. Tracheid anatomy in larch seedlings under long days (Group A). Note the sustained earlywood type (EW) anatomy (between arrows). FIG. 3. Tracheid anatomy in larch seedlings under short days (Group B). Note the sustained latewood type (LW) anatomy and the inactive cambium (IC). FIG. 4. Tracheid anatomy in larch seedlings of Group D. Note the band of latewood (LW) formed during short-day exposure, followed by earlywood type tracheids (EW) formed during long-day exposure. FIG. 5. Tracheid anatomy in larch seedlings formed in response to water stress (arrows). FIG. 6. Tracheid anatomy in a severely defoliated larch tree. The typical latewood band is absent. FIG. 7. Tracheid anatomy across three annual rings in a severely defoliated larch tree. The year of defoliation was 1962. FIG. 8. Tracheid anatomy in a severely defoliated larch tree. Note the differences in wall thickness and degrees of collapse between tracheids, suggesting "inter-tracheid" competition for the limited food supply.

Zimmermann 1964). The following physiological processes, related to wood formation, are influenced by growth regulators: cambial activity (including cell division, cambial dormancy), differentiation of cambial derivatives, cellular anatomy and dimensions, and the chemical composition as well as microfibrillar orientation in cell walls. Growth regulators are believed to play a key role in the mediation and transmittance of climatic signals to the cambium.

Experiments and Field Observations

LABORATORY EXPERIMENTS: PHOTOPERIODIC AND DROUGHT TREATMENTS

Two sets of laboratory experiments were conducted using 2-yr-old eastern larch (*Larix laricina* (Du Roi) K. Koch) seedlings. In the **photoperiodic treatments,** the effects of short days (SD) and long days (LD) on cambial activity and xylem development were studied in 40 seedlings. SD treatment was provided in a growth chamber regulated for 10-h day length, 16.14×10^3 lux light intensity, and temperatures of 25°C day and 15°C night. LD treatment was provided in a greenhouse, where sunlight was supplemented with artificial illumination to obtain 16-h day length. Unfortunately, temperatures in the greenhouse varied more widely than in the growth chamber (e.g., day temperatures ranged from 25 to 29°C, and night temperatures from 15 to 19°C).

At the beginning of the treatment, all seedlings were actively growing under long days. To "mark" the xylem at the beginning of the treatment, two compression wood marker arcs were induced in each seedling according to a method suggested by Kennedy and Farrar (1965). The photoperiodic treatments were maintained for 12 wk according to the following schedule:

Group	Weeks: LD-SD	No. of Seedlings
A	12 LD (controls)	10
B	12 SD (controls)	10
C	5 SD + 7 LD	10
D	7 SD + 5 LD	10

Seedlings in groups C and D were switched from short- to long-day photoperiods after 5 and 7 wk, respectively. At the end of treatment, all seedlings were destructively sampled, cross sections were cut from their stem segments and the course of xylem development was studied microscopically.

In **drought treatments**, the effect of artificial water stress on xylem development was investigated in actively growing 2-yr-old eastern larch seedlings. Water stress was created by supplying only half (100 ml) the daily irrigation quota and only once every 5 d. Ten seedlings were exposed to this drought regime. Ten controls received regular daily irrigation (200 ml water with complete nutrients). At the end of 20 d, all seedlings were destructively sampled and their xylem development studied microscopically.

FIELD OBSERVATIONS: IMPACT OF DEFOLIATION ON WOOD FORMATIONS

A 40-yr-old stand of European larch (*L. decidua* Mill.) was severely defoliated by the larch sawfly (*Pristiphora erichsonii* (Htg.)) around midsummer 1965. Over 70% of the trees in the stand were affected. It was postulated that the defoliation would offer a unique opportunity to investigate its impact on wood formation and xylem development. Consequently, 16 trees (8 defoliated and 8 non-defoliated) were destructively sampled, and disks were cut at height levels of 1.2, 5, and 10 m for microscopic observations. At the breast height position, only the transverse wall area of tracheids in five radial files was measured, across the entire current annual ring, and arithmetic means were computed and plotted. Anatomical observations concerned ring width, earlywood/latewood features, cross-sectional shape and wall thickness of tracheids. Some observations were recorded photographically.

Results and Discussion

PHOTOPERIOD

Observations of the seedlings and the anatomical characteristics of their xylem confirmed that photoperiod plays a decisive role in the regulation of extension growth and cambial activity. Long days favored continued shoot extension and the production of earlywood tracheids (i.e., large radial diameters and thin walls). Short days, on the other hand, were associated with the cessation of extension growth, the formation of latewood tracheids, and ultimately the cessation of cambial activity (Figs 2 and 3). These SD effects were apparent in spite of optimal temperature and moisture regimes for growth.

Transferring two groups of seedlings (C and D) from short to long days brought about fairly rapid changes in cambial activity and xylem anatomy. Cell divisions in the cambial zone resumed, and the anatomy of new tracheids was of the earlywood type (Fig. 4).

Results can be interpreted in light of the "hormonal regulation" of xylem development. Actively growing apical meristems and young leaves are generally credited with the production of indigenous auxins which promote cambial activity and the formation of earlywood type xylem structure. Short days are believed to retard the synthesis of auxins and facilitate the production of inhibitors. Larson (1960), Wodzicki (1964), and several other investigators made similar observations about the indirect effects of photoperiod on cambial activity and wood formation. Apparently, light influences both the quantitative and qualitative aspects of tree growth. Its quantitative effects on wood formation are mediated through variations in net assimilation rates, with impacts on ring width and cell wall thickness. The qualitative effects may be indirect, and manifested by different proportions of earlywood/latewood.

WATER STRESS

Microscopic examination of xylem anatomy in the stem of seedlings exposed to moisture stress indicated both direct and indirect effects. A fairly wide band of tracheids was affected (from 16 to 20 cells radially; Fig. 5). The width of the affected zone may imply that many cells were in different stages of their development (i.e., lignification, wall thickening, enlargement). Double staining for lignin and fluorescence microscopy both revealed incomplete lignification of a band of tracheids on the pith side. This band, two to three cells wide, was apparently prevented by moisture stress from completing its lignification. A much wider band of tracheids (five to eight cells) failed to complete the normal course of secondary wall thickening. Several of these thin-walled cells collapsed. The final band of tracheids (four to eight cells) was prevented from reaching the usual radial enlargement, ultimately resulting in a "false ring."

Morphologically, it was observed that drought interrupted shoot extension growth, and the growth of needles. These events, in turn, probably caused a reduction in auxin availability to the cambium in the treated seedlings. These observations agree with the interpretation of Larson (1963) who proposed that drought directly influenced the growth of the terminal meristems and only indirectly the tracheid diameter through the intermediate action of auxin. On the other hand, the presence of thin-walled tracheids appears to support the dual-effect (i.e., direct and indirect) hypothesis of Kramer (1964) and Zahner (1963).

Seedlings of the control groups continued to form only earlywood type tracheids during the experiment.

DEFOLIATION

The most dramatic observation in defoliated trees was the absence of a wide latewood band of thick-walled tracheids normally characteristic of larch (Fig. 6). Instead of thick-walled latewood cells, a band of tracheids with very thin walls (some collapsed) was evident. Harper (1913) also noted the absence of latewood band in the annual ring of the defoliation year in European larch.

Nondefoliated (i.e., control) trees showed the ring pattern typical of larch (i.e., distinct earlywood and latewood bands, with abrupt transition).

Examination of earlier rings revealed that the larch stand under study had suffered repeated defoliations in the past. The last severe defoliation comparable to that of 1965 occurred in 1962. The anatomical effects of the 1962 defoliation were also examined and the pattern was found to be similar to that of 1965 (Figs 7 and 8). For example, secondary wall thickening was retarded in a wide band of tracheids (about five to seven per radial file) and several of these thin-walled tracheids collapsed. The amount of latewood formed was either greatly reduced or completely prevented in the annual increment of the defoliation year, and ring width was also greatly reduced (as much as 50% compared with previous annual rings of the same tree). The width of at least two subsequent annual rings was also reduced. These effects were more severe in the middle and lower portions of the bole than in the crown portion. This pattern might be explained by the closer proximity of the crown portion to the source of photosynthate.

Another significant difference in wood anatomy of defoliated compared with nondefoliated trees is manifested in the reduction of cell wall area across the annual ring since the time of defoliation (Fig. 9). The following interpretation is offered for these results. The deprivation of differentiating tracheids from the vital food source prevented the completion of secondary thickening in those xylem daughter cells that were in the phase of secondary wall formation. Some of these cells later collapsed. These results indicate that the differentiating tracheids, especially those that are just entering the phase of secondary wall thickening, depend on a continuous supply of organic nutrients. Even a temporary interruption may prevent the tracheids from fully completing secondary thickening. When cross sections of both defoliated and nondefoliated trees were examined in polarized light, it became evident that in defoliated trees the S_2 layer of the secondary wall was either greatly reduced or absent, and the S_3 layer was consistently absent from tracheids that matured during or after defoliation. Although the absence of the normally thin S_3 layer makes little or no difference to the mechanical strength of wood, a very thin or absent S_2 layer must certainly reduce overall mechanical strength.

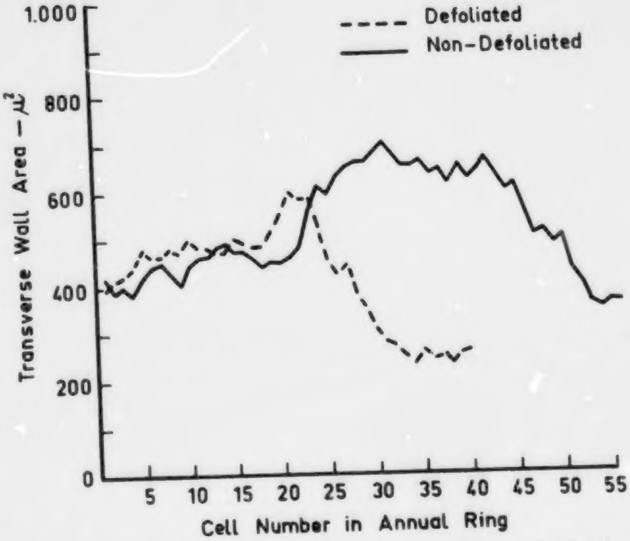


FIG. 9. Variation in transverse wall area across an annual ring in a defoliated and nondefoliated larch tree.

A unique aspect of these observations concerned the intertracheid competition for nutrients. Among the thin-walled and collapsed cells, there were tracheids that had somehow gleaned a sufficient amount of nutrients to form thick secondary walls which prevented their collapse (Fig. 8), suggesting that there was competition among differentiating tracheids for food substances.

The overall distribution of transverse wall area per tracheid, which is positively correlated with wall substance per tracheid, showed a decreasing pattern for cells that matured during and after defoliation. Bethel (1964) suggested that the amount of wall substance of a tracheid is probably a function of the cell's parentage and, therefore, more or less constant for xylem daughter cells having a common parentage (i.e., cells in a radial file). Larch observed in the present showed a different pattern. In non-defoliated trees, transverse wall area was more or less constant for earlywood tracheids at about 450 μm^2 per cell, but it increased sharply for latewood tracheids to about 650 μm^2 except for the last 7–10 cells in a radial file, for which wall area decreased. In defoliated trees, on the other hand, cell wall area was more or less constant for earlywood tracheids at about 450 μm^2 per cell, but decreased sharply for those tracheids that were prevented from normal secondary thickening by defoliation.

Conclusions

Photoperiod influenced both the quantity and quality of wood formed in larch seedlings in laboratory experiments. Long days (i.e., 16-h day length) favored the production of earlywood type tracheids. Short days (10-h day length) facilitated the production of latewood, and within 5 wk the cessation of cambial activity.

Drought (i.e., water stress) had both a direct and indirect effect on wood formation in seedlings. Cell enlargement, wall thickening, and lignification of developing tracheids were adversely affected by drought.

Defoliation of a 40-yr-old larch stand by the larch sawfly prevented the formation of latewood in the year of defoliation. Ring width was significantly reduced in two subsequent rings. Tracheids, which were in different stages of formation during defoliation, were prevented from completing their normal development. Particularly notable was a severe reduction in secondary wall thickening.

Results of both laboratory experiments and field observations fitted the theory of limiting factors, that is, a factor that falls below an optimal range will set the pace for physiological processes that determine the differentiation and maturation of wood cells.

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Effects of Climate on Wood Harvesting and Transportation Systems in Canada

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Abstract

Forest harvesting operations from stump to roadside and the transportation of wood to mill are performed under a wide range of climatic conditions affecting the site or road conditions, the design, selection, and maintenance of the machines used, and the planning of these operations to match the forest management objectives. Some selected examples of these interactions are presented and some recommendations for the type of climatic information desirable to optimize these operations or to make them more environmentally sound are discussed.

Résumé

Les opérations de récolte du bois, depuis l'abattage jusqu'au transport en bordure d'une route et enfin à la porte de l'usine, sont exécutées dans une vaste gamme de conditions climatiques qui influent sur l'état de la station ou de la route, sur la conception, le choix et l'entretien des machines utilisées et sur la planification de ces opérations qui doivent respecter les objectifs d'aménagement forestier. Les auteurs présentent des exemples de certaines de ces interactions et formulent des recommandations à l'égard du type de données climatiques dont il faudrait disposer pour optimaliser ces opérations ou pour les rendre plus écologiques.

Introduction

Canada is, above all, a northern country. To find similar conditions elsewhere one must go to Scandinavia or to parts of the northern USSR. Finland and Quebec and Norway and British Columbia are natural pairs. Canadians hardly need convincing that their climate is almost glacial. No people on earth have a more severe winter to complain about, latitude for latitude. The most important climatic events affecting the Canadian landscape were the Pleistocene glaciations which have modified and shaped our physical landscape.

Foresters and land users know that our forests are generally not randomly distributed; they are the result of specific and quantitative combinations of climatic, biotic, topographic, and parent material factors, all modified by time. However, this direct cause–effect relationship that undoubtedly exists remains to be demonstrated in many areas. Short of all the detailed quantitative information, landforms, soils, and vegetation patterns have played and are still playing an important role as indicators in recognizing similar forest units on the ground, using the subdivision approach (from above) instead of the association (from below) or cause–effect relationship.

For example, the forest regions of Canada described by J.S. Rowe (1972) are the obvious large units of forest description that all field workers recognize. These units serve as a framework for more detailed studies and for the recording of past management experience which could serve as guidelines for similar areas within the same region to eventually build a management data base. In Canada, climate plays an important role in the planning and the execution of wood harvesting and transportation operations. The necessary climatic information is derived from local weather stations and from interpreting the land features integrating the effect of climate over time. Some major research efforts are on-going at FERIC to better match our technology to our year-round climatic conditions. Areas of improvement in using and providing forest climate-related data to optimize forest harvesting and transportation systems, while being environmentally sound, are suggested.

Forest Climate-Related Data in Planning Harvesting and Transportation Operations

At the planning stage, the forest manager refers to climatic data and to the soils, landforms, and vegetation features expressing the effect of climate on the forest site. The climatic data are obtained directly from local weather stations, or more commonly, data from nearby stations are used to provide some information about the conditions to be expected at the dataless site. A short record of information may be needed for a specific purpose, or it may be desirable to establish a semipermanent station to collect records for determining long-term climatic statistics for a location. Table 1 gives some examples of how climate affects the planning of harvesting and transportation operations. As to the more indirect information, it is obtained through recognized interpretation techniques such as aerial-photographic interpretation indicators of the short- and long-term interactions between the land and the climatic conditions prevailing in the area. For example, photointerpretation techniques based on landform features, gully shape, and drainage patterns reveal soil texture such as sensitive lacustrine silt or gravel sources (esker and kames) for road construction. Floodplain zones can be identified thus avoiding the construction of permanent buildings in such hazardous areas. Soft ground areas or wet sites can be delineated and followed by field visits to refine the information. Drainage basin analysis generates an estimate of the number and size of culverts and bridges based on appropriate return period stormflow. Detailed soil descriptions will give soil drainage classes and possibly the seasonal variation of the water table.

A good example of how climate can influence the planning of harvesting and transportation of wood is the Queen Charlotte Islands project of FERIC, which is used here as a case study.

Case Study: Effects of Climate on Harvesting Operations on the Queen Charlotte Islands

Climate has created a valuable forest resource along the coast of British Columbia. However, the climatic conditions

TABLE 1. Some effects of climatic variations in the planning of harvesting and transportation operations (- disadvantages; + advantages).

	Effects on harvesting activities			Effects on transportation activities		
				Roads		
Climatic conditions	Selection of equipment	Accessibility	Maintenance	Location	Building & maintenance	Transportation
a. Precipitation						
• High rainfall	- Equipment creating less soil disturbance to reduce erosion and damage to site, especially on slopes.	- Low ground-bearing capacity sites have reduced access or are excluded for environmental reasons.	- Could lead to higher grit content in furnish (mud attached).	- Avoid erosion-prone areas (clayey soils).	- Hydraulic design of culverts and bridges.	+ Timing for river-driven wood.
	- Better flotability required (i.e., wide tires).	+ Reduced fire hazard, increasing the number of working days.			- Maintenance schedule.	
	- Increased ground disturbance leading to poorer regeneration and productivity.	- May cause operational shutdown.				
• Snow depth	- Machines adapted to deep snow conditions.	- Reduce access (close down). Affect scheduling of operations.	- Access to machines limited. (Longer delays to be expected.)		- Snow removal equipment and scheduling.	- Some delays and shutdowns to be expected with truck transportation.
b. Air temperature						
• Cold Weather	- Equipment must be able to operate in cold weather (machine start-up).	+ Firms up surface for access to wet ground.	- Breakdowns are more frequent, higher parts inventory and maintenance costs.	- Ice roads and bridges increase access.		- Selection of proper fuels and lubricants.
			- Selection of proper fuels and lubricants			- High maintenance costs.
• Freezing and thawing effects (day & night)					- Higher maintenance cost. Frozen culverts can cause some serious maintenance problems.	
• Heat	- Machines can overheat.	- Some sites may be drier and more accessible.	- Hydraulic breakdowns usually more numerous.			- Selection of proper fuels and lubricants.
	- Consider air conditioning units.	- Increase fire hazard (operational shutdown).				
c. Wind (speed and gustiness)	- Harvesting pattern to minimize blowdown.	- High winds cause operational shutdown for the fallers.				
	- Helicopter logging excluded.					
d. Fog or low cloud cover	- Helicopter for logging or used for crew transportation has limited capabilities under these conditions.	- In mountainous terrain will cause operation shutdown.		- Helicopter pads should be located above the fog zone.		- Visibility reduced.
	- Visibility reduced especially on mountain logging.					

combined with the natural topographic setting have led to land management problems, especially on the Queen Charlotte Islands.

During the winter of 1978, a series of storms triggered landslides over much of the Queen Charlotte Islands. Originating on steep slopes, many slides deposited tonnes of debris in streams and onto valley flats. These events raised private and public concerns over logging practices on the islands and promoted a 5-yr multidisciplinary research program called the Fish/Forestry Interaction Program (FFIP) (Poulin 1984).

The studies were designed to supply basic data for forest management, to document the conditions that influence mass wasting on the Queen Charlotte Islands, and to recommend alternative practices that could reduce the potential for accelerated mass wasting on logging areas.

STUDY LOCATION

The Queen Charlotte Islands form a rugged archipelago approximately 130 km west of the north coast of British Columbia. The area is dominated by rugged mountain ranges in the west and south and lowland plains in the northeast. As a result of tectonic uplift and glaciation, the mountain region has generally oversteepened slopes. A temperate coastal maritime climate, high annual rainfall (1150 mm on the east coast and 4300 mm on the west coast) over 200 d/yr with measurable precipitation and 70 to 80% falling in the fall/winter months of October to April, strong winds, and an active seismic regime contribute to the natural instability of the area (Calder and Taylor 1968, Alley and Thompson 1978, Karanka 1985).

The mild, moist climate has created an ideal site for growing trees. The Queen Charlotte Islands contain some of the largest trees in North America (Sitka spruce, western hemlock, western red cedar, and yellow cedar) and some of the most productive sites in Canada. The huge trees require large harvesting equipment to move them from the stump to roadside and the roads must be wide to move this equipment. The mild climate also creates an environment that allows for rapid development of natural vegetation over logged or denuded areas. This vegetation assists in binding the soil masses together.

The abundant rainfall supplies water for hundreds of small coastal streams, which provide spawning and rearing habitat for important sport and commercial fisheries. The streams are generally short (less than 2 km long) and have steep gradients.

Logging Influences

Strict logging guidelines are followed that prevent the deliberate destruction of fish habitat by logging. Logging or roads on steep slopes or around the headwall areas of the streams, however, may cause landslides that can travel downslope and enter the area of fish habitat or can enter a steep V-shaped gully, travel the length of the stream and either scour-out or deposit debris on top of fish habitat. If landslide debris should be held up within the channel, above habitat, it can remain as a source of fine sediment, organics, and gravel for many years. When heavy rainfall events occur, water levels rise and can move the dams of material to lower locations.

Two of many important questions that were asked at the beginning of FFIP were:

1. Have the weather patterns changed during the past few years, so that more and heavier rainfall is occurring than during previous periods? Increased rainfall would help explain why there was an apparent increase in landslides.

2. What can logging companies do to reduce the potential for landslides to occur? This assumes that the number of landslides could not be reduced below the natural level of 1.1 failures/km².

Climatic Study

In a report prepared for FFIP, Karanka (1985) reviewed the climatic data available from weather stations on the Queen Charlotte Islands to determine (as part of the study) precipitation trends. Karanka concluded that there is an alternation between periods of above normal fall/winter rainfall and temperature but below normal snowfall (Type I), and periods of below normal fall/winter rainfall and temperature but above normal snowfall (Type II). Table 2 shows when these periods occurred.

The fluctuations result from shifts in the mean position of the fall/winter stormtrack across the northeastern Pacific. Fall/winter rainfall at the beginning of the FFIP study was thus heavier than during the previous drier period.

Logging Practices

During the 1974/75 to 1983/84 wet period, logging also began to shift from the flat or gently sloping valley-bottoms to the steeper mid-slopes. The first signs of potential slope instability began to occur in 1974/75 on the steep slopes as landslides at road edges and within yarding settings. Before this, landslides were caused more by soil that had been simply pushed over the roadside.

TABLE 2. Periods of climatic alternation.

Type 1 Above normal fall/winter ppt. and temp.; below normal snowfall	Type II Below normal fall/winter ppt. and temp.; above normal snowfall
1923/24 to 1945/46	1946/47 to 1956/57
1957/58 to 1963/74	1964/65 to 1973/74
1974/75 to 1983/84	

FERIC has examined historic and recent landslides and logging operations on the Queen Charlotte Islands to recommend methods that can be used to minimize the potential for landslides to harm fish habitat or destroy valuable growing stock. Climate plays a major role in initiating landslides by supplying water in the form of rainfall that saturates the soil and regulates the relative rates of recharge, transmission, and evapotranspiration in hillslope soils that ultimately influence their stability. When saturated soils are combined with the steep slopes and a deterioration of soil strength as a result of tree-root deterioration caused by cutting of the trees, the end result is a state of marginal stability that could be upset by yarding disturbance such as uprooted stumps, blown-over trees at the cutting boundary, or by entry of water to subsurface soil levels as a result of root decay (Sidle et al. 1985, Krag et al. 1988, Sauder 1984). The road system itself is a chronic source of potential landslide problems.

What then are some of the proposed methods of logging these steep slope settings that will reduce the potential for landslides?

1. Partial cutting. A thrifty root network could be maintained on hillslope settings if only small openings or individual trees were selected for logging rather than clear-cutting large areas. Partial cuts or small openings are not practical on the Queen Charlotte Islands because the exposed stands are not windfirm and the high velocity windstorms would increase the amount of wasted wood as a result of windthrow. In addition, the large logs would create substantial damage to the residual stand as they were removed, and road lengths would have to be increased to access additional areas of timber.

2. Long-line skylines or helicopters for logging. These methods assume road lengths could be reduced on the hillside, thus reducing the potential for road-induced landslides. These systems are expensive to operate, require high value wood, and cannot economically clean out debris from gullies or streams. They also leave areas that are expensive to plant or to treat silviculturally in the future because of the lack of road access. Helicopters cannot operate during high winds or when cloud cover is low — conditions that occur frequently during the fall to spring months.

The most practical techniques for logging the steep slopes are:

1. Use systems and techniques that are well understood, productive, and economical.

2. Intensively plan the area so that road lengths are minimized and logging systems are matched to the terrain they most suit. Minimize the lengths of standing timber exposed to winds along cutting boundaries.

3. Stop logging on steep, potentially unstable slopes during periods of high rainfall.

4. Ensure drainage structures remain open on active

TABLE 3. Impacts of climate on the efficiency of forest harvesting operations (– disadvantages; + advantages).

Climatic conditions	Impacts on forest harvesting operations			
	Machinery	Operators & mechanics	Maintenance	Timing of operations
a. Precipitation				
• High Rainfall	– Start-up problems (especially chainsaws).	– Slippery, dangerous conditions causing some shutdowns.	– Access to the broken machine is more difficult as the ground gets softer.	+ Reduced fire hazard.
	– Poor mobility (sinkage, rutting).	– Uncomfortable (rain gear).		– Scaling is more difficult.
	– Visibility reduced especially if windshield wipers absent and windows smeared.	– Visibility reduced.		– Some sites are inoperable. – Some sites are not accessible because of surrounding low ground bearing capacity.
• Snowfall (wind) and snow depth	– Mobility reduced causing delays.	– Snow on trees make manual felling unpleasant.	– Reduced access.	– High snow will reduce access especially for manual operations (close down).
	– Visibility reduced (shutdown).	– Increased slippage risk for manpower.		
		– Major terrain obstacles not seen by operator.		– Snow cover obscures trees, bunches, and piles, calling for hotter operations so wood is not lost.
b. Air temperature				
• Cold weather	– Machine start-up (keep engine running between shifts).	– Heavier clothing reduces physical agility.	– Higher maintenance costs — increased breakage.	+ Firms up ground for access to wet ground.
	– Increased tire puncture.	– Increased slippage.	– Mechanics cannot protect their hands properly.	
	– Increased butt shatter with shears.	– Increases the risk of "white-finger" disease.		
	– Wood breakage during various phases (especially mechanical delimbing).			
	+ Delimbing ease is increased.			
	– Piles freeze together (loading, delimbing).			
	– Loss of biomass during skidding and at landing.			
• Heat	– Machine overheating.	– Enclosed machine cabs can accumulate too much heat, causing operator discomfort and loss in productivity.	– Increased maintenance.	– Increased fire hazard (operational shutdown).
		– Direct sunlight through cabs' windows create glare and local hot spots on face & eyes.		+ Some sites may become drier and thus operable.
		– It is difficult to cool-off while wearing standard protective equipment.		
c. Wind (speed and gustiness)	– Problems in directional felling, especially on slopes.	– Breaking tops are often fatal especially in diseased stands.		– Operational shutdown.

(Continued)

TABLE 3. Impacts of climate on the efficiency of forest harvesting operations (- disadvantages; + advantages). (Concluded)

	Impacts on forest harvesting operations			
Climatic conditions	Machinery	Operators & mechanics	Maintenance	Timing of operations
d. Fog	- Loss of productivity because of disorientation in skidding.	- Reduces visibility.		- Operational shutdown.
		- Workers on forest might not be seen by approaching machines.		
		- Audio warnings are not clear.		
		- Difficult visual inspection of standing timber before felling.		

roads, and reduce the need for drainage structures to carry away water on roads where logging is finished. Abandoned roads should be open to some form of vehicular traffic, while minimizing the need for maintenance. Road design and construction must acknowledge the heavy rainfall that occurs by properly managing water by installing adequate drainage structures such as ditches, culverts, and bridges. The potential for roads to consolidate water from two or more sources should be minimized by designing proper drainage crossing.

5. Plant areas where natural regeneration may be low immediately after logging. Most areas are naturally restocked within 3 yr on the Queen Charlotte Islands and planting is primarily used to supply species diversity. Planting establishes a thrifty root network that binds the soil masses together.

6. Utilize stream and hillside restoration or rehabilitation techniques that reduce the losses or reduce the time period a stream or forest site may be out of production.

7. Identify the values of resources that may be affected by potential landslides so that cost/benefit analysis can be prepared for alternative logging systems.

Climate plays an important part in influencing forest operations on the Queen Charlotte Islands. The mild climate allows for rapid growth of new vegetation that can be used to assist in increasing the stability of the hillside following logging. General logging practices must consider the effect water has on initiating landslides and to manage the water that drains the land so that its routes are not disrupted nor channels concentrated onto areas not able to handle it. Attention must be paid to areas where logging is finished so that drainage structures or techniques are used that minimize the need for maintenance and allow for vehicular access.

Logging systems that are matched to the terrain and allow for profitable logging will reduce the potential for yarding initiated failures. Identifying the resource values affected by potential landslides allows for assessment of practices and costs of alternatives to avoid or minimize risks.

Planning logging openings so they minimize the potential for windfall along the cutting boundary while also minimizing road lengths will reduce the potential for landslides. Intensive planning can identify potential problem sites at an early stage and can propose techniques to prevent a landslide from occurring.

Impacts of Climate on the Productivity of Harvesting Operations

Climate affects the productivity of harvesting operations. The conditions may be favorable or on the contrary climatic events can significantly reduce the efficiency of harvesting operations or simply preclude them altogether. Table 3 gives some of the impacts of climate on the efficiency of forest harvesting operations.

Examples of the technology developed and introduced by FERIC to the Canadian forest industry to cope with some of the negative effects of climate on harvesting operations include:

a) Increasing Off-Road Mobility in Soft Wet Ground Operations. Five years ago, FERIC introduced the first set of high flotation tires to the forest industry and the manufacturers. The results were spectacular. Skidder productivity was increased by up to 60% in soft, wet ground operations, and fuel consumption was reduced by up to 40%. Ground disturbance is virtually eliminated even after repeated passes, and damage to advanced regeneration is reduced significantly. Today there are more than 400 tires in use in the Canadian forestry industry and the market projections call for approximately 1600 by 1987. The potential application of the high-flotation tire technology for prime movers used in scarification work will be investigated within FERIC's 1987 work program.

b) Reducing Butt Shatter of Saw Logs Especially Under Cold Weather Conditions. Through its advisory committee FERIC was asked to investigate the butt shatter of saw logs. The solution was found in the circular saw concept developed in cooperation with a member company. This innovative technology was picked up by equipment manufacturers who are now offering it under various configurations.

c) High-Mobility Modular Machine System for Wood Harvesting. The design, fabrication, and testing of the FERIC forwarder was the first step towards developing a new high-mobility modular machine system for wood harvesting. The mechanical drive is replaced by a hydrostatic one, thus reducing the number of moving parts resulting in lower maintenance especially in cold weather or muddy sites.

d) Component Life and Maintenance History of Logging Machines. This is an on-going project at FERIC by which repair history data for forestry equipment are being

TABLE 4. Impacts of climate on the efficiency of truck transportation operations (– disadvantages; + advantages).

Climatic conditions	Effects on truck transportation operations including roads				
	Drivers	Tractor-trailer assembly	Payload and load security	Road conditions	Road maintenance
a. Precipitation					
• High rainfall	- Visibility reduced.	- Poor traction. ± Lower speed.	- Reduced payload (= 300 kg/trip) because of mud being deposited under the tractor-trailer assembly.	- Slippery (hazardous). - Muddy and round surface deterioration resulting in higher rolling resistance therefore higher fuel consumption. No dust on the road.	Higher maintenance resulting from washout materials from the road (shutdown).
• Snowfall (wind) snow depth	- Visibility reduced (shutdown).	- Poor traction. - Lower speed.	- Reduced payload (= 600 kg/trip).	- Slippery. - Higher rolling resistance.	- Snow-removal equipment.
b. Air temperature					
• Cold weather	- Increased slippage around the unit.	- Engine power and fuel consumption modified with the intake air temperature. - Engine life, power, and fuel consumption are influenced by engine coolant, oil, and fuel temperatures. - Lubricants are generally thicker at low temperature (churning losses and driveline friction) causing higher fuel consumption. - Tire operating-temperatures will influence fuel consumption. - Low ambient temperature changes the flexibility of any metallic parts (suspension leafs become more rigid).	- Frozen wood more likely (especially jack pine) to slip off the load. - Suspension is more rigid, therefore transmitting more vibrations to the load.	+ Frozen road surfaces offer less rolling resistance. + Ice roads and bridges are inexpensive.	
• Heat	- Require air conditioning unit.	- Engine runs less efficiently with higher fuel consumption. - Transmission and rear axle oils may overheat causing wear and tear to the components. - Tires may run too hot therefore having higher fatigue and shorter lives.		- Dust will reduce visibility.	
• Freezing and thawing effects (day & night)	- Reduced weight allowance, i.e., reduced payload.	- Rough road leading to higher vibration affecting load stability.	- Poor road quality.	- Poor road quality.	- High road maintenance. - Culverts are freezing at night, causing drainage problems during the day.
c. Wind (speed and gustiness)	- Combined with rain and/or snow, it will reduce visibility.	- High side wind may become a safety hazard especially if the unit operates on slippery roads. - Chill factor is important in overcooling the engine, transmission, and gear oils.			
d. Fog	- Reduced visibility.	- Speed reduced. - Obstacles less visible.			

gathered. The objectives of the study are to identify the parts and labor costs associated with maintaining a mechanized logging/transport system, to determine relative component life and its effect on machine availability and maintenance costs which are related to seasonal variations of our climate.

Impacts of Climate on the Efficiency of Truck Transportation Operations, Including Roads

The influence of climate on the road systems is certainly obvious because of the associated high maintenance and operational shutdown. The impacts on the transportation unit are more subdued but nevertheless important. Table 4 gives a general summary of the impacts of climate on truck transportation operations, including roads.

Examples of the research results obtained by FERIC's research program in the Secondary Transportation area are:

a) Influence of Winter Roads on Fuel Consumption. A frozen winter gravel road offers less rolling resistance than a good and dry gravel road under summer conditions, therefore reducing the fuel consumption in the order of 25%.

b) Influence of a Five Day Rainfall Event on the Rolling Resistance of a Gravel Road. The fuel consumption of a tractor-trailer unit was measured daily on a road being submitted to heavy rain for 5 consecutive days. The difference in fuel consumption between the 1st and 5th day was about 12%.

c) Effect of Driveline Oil Temperature on Fuel Consumption. With the integrated instrumentation package developed by FERIC, engine and driveline oil temperatures were measured and found too low in winter operating conditions. Standard and semi-synthetic driveline oils under those conditions were compared, and the difference in fuel consumption was 3.8 L/100 km which represents 8.5% of the total fuel consumption. More significantly, raising the temperature in the driveline under winter conditions represents a potential saving of about 20%. FERIC has investigated this concept with a member company by insulating the differential. The findings are summarized in a technical note entitled "Insulate to Optimize Viscosity of Gear Oils in Trucks."

Conclusions

Climate plays an important role in the planning and the efficiency of harvesting and transportation operations of the Canadian forest industry. Suggested areas of improvements include:

- Ensure that the existing climatic data are presented to the forest manager in such a format that they are easily accessible and usable.
- Improve the correlation of existing climatic data to the existing land features so they can be used as indicators for the dataless sites.
- Improve weather forecast for remote forested areas, especially for low temperatures, deep snow (> 1 m), number of days below-freezing temperatures, high intensity rainfall, rainfall–fire hazard forecasting, wind, and fog.
- The effects of climate on our operations must be better understood to promote higher efficiency through improved technology and methods.
- The potential of remote sensing techniques such as thermal infrared imagery should be investigated further.

Climate-related data are best used at the planning stage of forestry operations. The move towards intensive forest management will call for more precise climatic information to understand our forest ecosystems regarding their influence on water regime, variations in evapotranspiration rates, high temperature on south-facing slopes, etc. The forest manager will gradually acquire a better understanding of the cause–effect relationships of climate on the forest and the equipment used, and will hopefully be more efficient in managing this valuable Canadian resource.

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Actual and Potential Value of Climate Information in Forest Management

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Abstract

Day-to-day weather information is routinely considered in conjunction with a multitude of activities related to forest management. Moreover, the usefulness of such information is readily acknowledged, although quantitative assessments of its value are seldom made. On the other hand, the value of climate information, that is, information derived from historical data or information expressed in the form of climate (e.g., monthly, seasonal) forecasts, is not widely appreciated in the forest management context. In this paper, the use and value of climate information (especially climate forecasts) are approached from a decision-analytic perspective. From this viewpoint, climate information would be used and would acquire value only when it provides a basis for more effective decision-making. Examples drawn from decision-analytic studies of the value of weather and climate forecasts in fire management and in the agricultural sector are used to illustrate the actual and potential value of such information. The applicability of this methodology to decision-making problems involving the use of climate information in forest management is discussed.

Résumé

L'information météorologique quotidienne est normalement examinée en conjonction avec une multitude d'activités liées à la gestion forestière. De plus, l'utilité d'une telle information est facilement reconnue, bien que les évaluations quantitatives de sa valeur soient rares. Par contre, la valeur de l'information climatique, c'est-à-dire celle provenant de données historiques ou de valeurs exprimées sous forme de prévisions climatiques (par exemple données mensuelles, saisonnières), n'est pas appréciée de façon générale en gestion forestière. Dans ce document, on aborde l'utilisation et la valeur de l'information climatique (particulièrement les prévisions) dans un contexte décisionnel-analytique. Considérée sous ce jour, l'information climatique n'augmenterait de valeur et ne serait utilisée que lorsqu'elle fournit la base d'un processus décisionnel plus efficace. Afin d'illustrer l'importance réelle et potentielle d'une telle information, on a recours à des exemples tirés d'études décisionnelles-analytiques de la valeur des prévisions météorologiques et climatiques dans les secteurs agricole et de gestion des incendies. On examine l'applicabilité de cette méthodologie à la solution de problèmes associés aux processus décisionnels qui comportent l'utilisation de l'information climatique en gestion forestière.

Economic Implications to Forestry of Future Climate Predictions

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Abstract

Long-term forestry planning has always assumed that the future will be the same as the past. For this reason possible long-term changes in biological and physical variables have never been factored into forestry decision-making. Given the wide differences in the views of the future of scientists, politicians, foresters, and economists, it may never be possible or practical to incorporate all these views or even one school of thought into today's forestry decision-making process. However, the successful outcome of even the most mundane of forestry decisions, such as what tree to plant where, depends on a host of biological and physical variables, and if these are subject to gradual progressive change over the course of a forest rotation, there could be intense downstream economic implications. The long-term economic consequences of rightly or wrongly predicting the future are discussed.

Résumé

On a toujours supposé dans le secteur de la planification forestière à long terme que l'avenir serait une répétition du passé. Pour cette raison, les modifications possibles à long terme des variables biologiques et physiques n'ont jamais été considérées comme des facteurs à intégrer au processus décisionnel en matière d'exploitation forestière. Vu l'écart considérable qui sépare les visions d'avenir des scientifiques, des hommes politiques, des forestiers et des économistes, il est probable qu'il ne soit jamais possible ou pratique d'intégrer tous ces points de vue ou même une seule école de pensée au processus décisionnel actuel dans le domaine forestier. Cependant, il ne faut pas oublier que même les choix judicieux les plus ordinaires, comme le plantage du bon arbre à l'endroit approprié, dépendent d'une foule de variables biologiques et physiques. Cependant, la modification graduelle de ces derniers au cours de la révolution forestière aura peut-être d'importantes conséquences économiques en aval. On examine les effets économiques à long terme des prévisions d'avenir justes et fausses.

During the last 2 d I have been impressed by the quantification and illustrations that have accompanied the learned presentations. Things now change. I have no charts, no graphs, or slides — in other words, no data. However, I will proceed to nail jelly on the wall and put a rainbow in a wooden box.

I have been asked to put an economic dimension on climate change predictions. First, I must confess that I have found this to be an impossible assignment. Second, there is virtually nothing in the literature on which to base any remarks I may make. This leaves me in a very naked position. I cannot cover my rear by quoting or interpreting some noted, respected, and published person. For these reasons, I have concluded that at best I can only speculate, and then pose potential concerns to today's forest managers.

For the purpose of my paper I am defining climate as the summation of numerous annual weather patterns. Please remember I am not a climatologist or a meteorologist, but a simple forest economist trying to come to grips with a massive amount of scientific data that has been provided in the last few days and that has appeared in the literature in the last decade.

Written history contains a mass of references to men and women trying to predict the future. In the not so distant past the predictors of the future were often held in fear and disdain by the general population. They were thought to possess powers beyond the mortal human. They resided on mountain tops, in caves, or were located at the far end of a dark murky alley. So what has really changed? The tea leaf reader and the soothsayer have given way to giant sophisticated models, and forecasting the future is now an acceptable occupation. Predictors now live in nice houses, drive nice cars, and look and at times act like normal people. However, the basic predictions remain the same no matter what technique is used. Predictors are trying to tell us what will happen in the future. Their predictions range in time frame from 10 min to several decades. The longer the term the more vague and generalized the prediction becomes. In the case of the economist, the smart ones have learned never to forecast something to happen before their retirement date or their death. It appears climatologists have taken a leaf out of the economists' book since most predictions of climate change are in the range of 26–60 yr.

The one thing I and many others have learned about medium-to long-term predictions or forecasts of the future is that they are invariably wrong. Despite this, predictions of climate change have become commonplace. The difficulty with these predictions is that they vary widely, some are contradictory and some have been severely challenged. Depending on the source, we have visions of Canada becoming warmer or colder, wetter or dryer, and the seas rising as much as 60 ft (18 m). However, there appears to be a majority of thought that sees our climate becoming 2–4°C warmer over the next 30–50 yr, and a modest increase in ocean levels. Rainfall patterns are also predicted to change significantly but here there does not seem to be any clear direction or consensus in these predictions.

Assuming for the moment that the prediction of a warmer climate is generally accurate, this, without doubt, will have a tremendous impact on the biological performance of our forests. Looking at the areas to the south of us where average temperatures approximate those being predicted for Canada, we can anticipate such things as an increase in our tree growth rate, a change in species composition and a northward movement of the tree line. Generally, all will have a positive economic impact but only in the long term. On the negative side, and before the positive benefits occur, there may be a change in the forest fire pattern. Knowledgeable people suggest this has already started to occur and, in the past 25 yr, evidence points to a changing pattern with fewer but larger fires in the Boreal Forest Region. Again on the negative side, insects and disease may spread more rapidly. The balsam woolly aphid, for example, has a range defined by minimum winter temperatures. If minimum temperatures increase, that pest could spread far faster than the forest ecosystem can adjust.

Turning again to the positive side of a warmer climate, some experts predict the melting of the polar ice caps would result in a rise in ocean levels and a subsequent saltwater flooding of large highly productive forest areas belonging to our economic competitor, the United States. Just imagine the impact this would have on the United States–Canada free trade talks of today. The headlines of the New York Times could read "CANADIAN ICE WATER FLOODS SOUTHERN STATES — COUNTERVAIL DEMANDED."

Foresters, like most professionals, have always looked backward in time to forecast the future. Normal yield tables, form class volume tables, and allowable annual cut estimates are all long-term quantifications, but all are based on past performance. Such things as fire danger ratings, insect damage forecasts, and spreading rates of tree disease are of shorter time frames but they are also based on past experience. Fortunately or unfortunately, the forester was never around eons ago when parts of Canada were warmer or colder. His measurements of those days would provide valuable input to understanding the biological uncertainties we may be faced with tomorrow. The little bit of dendrochronology research that was being done in Canada, I understand, has been phased out for what has been deemed to be higher priority research. In the eyes of an economist working with a resource having the time frame of a forest, this is extremely regrettable. Without a firmer knowledge base it is impossible to grasp, with any degree of precision, the changes that will occur in our forests. Such information is critical to long-term economic analysis.

It appears that warnings of climate change have fallen on many deaf ears. However, it may well be that the scientist has not communicated his message in the right fashion to the right persons. In any event, the prospect of climate change and its impending biological and economic impact has not been taken seriously by decision-makers. The simple truth is that the boardrooms and cabinets have not factored climatic change into decision-making at the economic, social or political levels. Possibly, this is because of the high degree of uncertainty and the contradictory views of what climatic changes will occur. Possibly, it is because the long-term view of the politician at its best is a mere 5 yr. The view of businessmen or industrialists may stretch as far as 20 yr or until a new investment is totally written off for tax purposes.

I asked my 20-yr-old daughter, who has a strong science orientation, if she had any concerns about pending climate change, and how it might impact on her future economic status. Her answer was "no." It seems her concerns are about figure skating, getting high marks in university, and being accepted into a quality medical school. My son, who is 28 and working in the oil business, said in a very casual fashion he hoped it would get warmer, and that it would not hurt the fishing. I admit this is not a good statistical sample, but perhaps you should all go home and ask your children the same question. They are the ones who will be living with the change, and they are the ones who may be able to solve the problems and capitalize on the opportunities. My limited data indicates your message of climate change is not getting through, and until it does, decision-makers will not consider the impact of climate change as a variable. This does not mean they shouldn't. Long-term investments are being made frequently and I believe climate change should be considered a prime variable. For example, Quebec is spending billions on northern hydro developments, but who is to say the rivers being dammed will continue to have their current flow levels. Canada is spending millions on reforestation, and who is to say we are planting the right tree on the right site. Buildings having a life expectancy in excess of 100 yr are being built on the basis the future will be the same as the past. Are the policies of several provincial governments not to aggressively fight forest fires north of such and such a line compatible with a warming climate? Is the decline of the sugar maple in Eastern Canada due to pollution or to climate change? All in all we lack the knowledge base to answer these and similar questions. I contend that much of our research efforts are spent on yesterday's problems rather than tomorrow's.

All I can suggest is that we have to be very careful. If the estimate of the future climate is wrong and if the wrong estimates are factored into decision-making, more economic harm than good will occur. Vast amounts of scarce economic and human capital could evaporate. If we make a decision on a scientific prediction of the future we must always ask "What if the scientist is wrong?" Unless the scientist can come up with more definitive projections based on a consensus of what climate to expect 50 yr hence, there is no way the economist can describe the economic consequences in terms of employment, gross national product, per capita income, or return on investment. These are the terms the decision-maker understands and sometimes reacts to with vision. But right now we are faced with a classic case of UNK-UNKS, which translated means unknown unknowns.

I have already retired, and since I continue to smoke I am told I am not long for this world. These two attributes entitle me to make long-term predictions to the years 2030 or 2050. But I am really out on a limb, since nothing I will be predicting can be defended with anything concrete.

Given a 2–4°C increase in average temperature,

Given rainfall will continue to be more or less distributed throughout the year on a month to month basis at reasonable levels,

Given that a hundred or so economic, demographic, and political factors don't go absolutely haywire, nationally or internationally, and

Given my gut and my talks with the stars have produced some rational input.

Besides my gut and the stars I should provide you with some insight into my unscientific method for assessing the economic implications of climate change. I drew up a separate positive impact list and a negative impact list for both the United States and Canada — a total of four lists. Some of the things itemized included evaporation rates, tourism, agricultural gains and losses, net forest growth, costs of a possible increase in ocean levels of 5 ft or so, construction and transportation costs, heating and cooling costs, immigration etc. All these were weighted and summarized in a highly subjective manner.

Every one of you could develop your own lists of impacts, your own weighting of positive and negative impacts, and your own summarization. If you are brave enough you could discuss your guesses and your results with friends and peers. I used this process to a degree and found it was fairly easy to identify areas of general agreement and areas of uncertainty, and also areas where my so-called friends said I was crazy. If you do not plan on working or living beyond, say, 20 or 30 yr, you may even be brave enough to make your results public and speak to a learned symposium like this one. In my opinion, the climate change predicted will result in some fairly severe negative impacts on the United States economy, and many positive impacts on the Canadian economy.

I believe the net benefits over costs of the predicted warming trend could result in an increase in Canada's per capita income, in real terms to the level where Canadians approach or equal the per capita income of the United States.

In other words, we will be given the chance to slowly close the economic gap that has always existed between the two countries. This is a tremendous opportunity. Forestry can play a part. Let's not blow our chance with lack of knowledge. The scientific community must provide the kind of information that can be translated at the macroeconomic level and then communicated to the decision-maker. But the bottom line and the fly in the ointment is, of course, UNK-UNKS, or unknown-unknowns.

Summmary

SESSION IV. CLIMATIC APPLICATIONS IN FOREST UTILIZATION AND ECONOMICS

Climate and Wood Quality

Basic wood properties are strongly influenced by climate. For example, the juvenile–mature wood transition, pulp properties, heartwood area, and sawlog quality vary in response to the climatic processes and silviculture treatment. Catastrophic climatic events are recorded within the tree leaving a permanent imprint on the maturation of wood cells. However, comparatively little attention has focused on wood quality relative to the attention focused on quantity of the wood supply within the management-planning framework. Yet quantity and quality variations are a function of climate and directly affect the wood supply management.

Therefore, it is recommended that:

1. forest growth and wood quality studies be combined with climatic technology to enhance wood supply management;
2. site-specific process studies that identify both the growth and wood density changes over time and their variability in space be encouraged. This is particularly important for selecting planning the characteristics of the new forest; and
3. computerized hardware and software development be accelerated to increase the application of wood density analysis into operational forest practices.

Harvesting/Transportation/Utilization

Synoptic forecasting can have an immediate cost-effective impact on day-to-day operational harvesting and transportation activities. Risk analysis of selected climatic events could significantly enhance regional harvesting and transportation planning. This technology is available but is not used to any great extent by the private or public sectors.

Wood (i.e., wood density) continues to serve the building industry, for example, in the construction of energy-efficient homes. The need for modification of traditional wood products to meet the new insulation requirements for specific climate regions and locations is readily apparent and reinforces the attention needed for basic wood properties and climate studies.

Therefore, it is recommended that:

1. synoptic forecasting and climatologies, risk analyses, and site-specific climate prescriptions be incorporated into harvesting and transportation activities to optimize operations; and
2. increased monitoring of specific utilization characteristics of the wood supply be encouraged in light of the industrial requirements for known wood properties.

Economic Value of Climate

Little attention has been focused on the cost-justification for integrating climate information into forest management. Yet synoptic forecasts for day-to-day operations and historical climate productivity models, for example, are regarded as having significant positive cost/benefit impacts.

Current efforts of forest economists to replace assumptions with good forest-climate data forces the forester and climatologist to integrate their efforts within an accountable framework to justify silviculture investments and timber production planning. Increased effort in this sector is required immediately with the marketplace as the focus.

Therefore, it is recommended that:

1. silviculture investments and timber production economics models be expanded to include the integration of climate for the optimization of forest-management solutions (the appropriate climatic data bases are currently available at the macro- and meso-planning levels); and
2. the forest climatology commmunity identify and cost-justify the impact of climate in operational management activities (this will involve the development of new methodologies).

Discussion

Climate and Forest Production

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Abstract

Climate in relation to forest production is viewed from two perspectives. The first, which is the one dealt with by the majority of participants, uses the factor approach. The second, marked by its virtual absence, is to start from the standpoint of the marketplace for forest products and then analytically arrive at conclusions concerning the relative importance of specific climatic situations or factors.

The importance of using both perspectives in relation to forest production in determining research and management priorities is discussed.

Résumé

L'étude du climat en rapport avec la production forestière est abordée sous deux angles très différents. Dans le premier cas, qui a été traité par la majorité des participants, une approche factorielle est utilisée. Dans le second cas, caractérisé par son absence à peu près totale, le marché des produits forestiers est le point de départ à partir duquel on progresse analytiquement vers des conclusions sur l'importance relative de situations ou de facteurs climatiques particuliers.

On traite de l'importance de l'utilisation des deux approches dans le contexte de la production forestière pour déterminer les priorités de recherche et de gestion.

There is an old story, undoubtedly apocryphal, that I think has a lesson for many scientists and professionals. It is about the traveller who is on his way to Boston but who in taking various shortcuts on backroads has become lost. Finally, he spies an old gentleman sitting on the verandah of a farmhouse close to the road. He stops his car out front and goes over to the old chap and asks him how he can get on the main road to Boston. The old man scratched his head and said, "Well, go down the road in the same direction you are going to a schoolhouse and then . . . ." He stopped there and puffed his pipe and then said, "No, you better turn around and go back about two miles to the crossroads and then turn to your left and go down that road to a church and . . . ." He stopped again, puffed his pipe and then said, "Young man, if I was going to Boston I wouldn't start from here!"

Too often in our professional and scientific activities and related thoughts we assume a particular starting point when given a specific objective. There are good reasons for this. In fact, our education and training to ensure effective and efficient analysis, diagnosis, and related practices and activities are largely founded on using set procedures and approaches so that there will be consistency, comparability, and an ability to follow logically the sequence of actions and related results.

Why then am I sounding a caveat? It is not because our present approach is not satisfactory, by and large. It is because as with virtually everything related to rules, procedures, and processes, there are occasions when their application can lead one astray not to a slight degree, but horrendously. I would suggest to you that when we consider the topic "Climate and Forest Production," many of us are in danger of starting from the wrong place, and therefore all the logic that we bring to the topic can be called in question.

Let us start with a consideration of forest production and its elements and then relate these to climate. In doing this the time frame is particularly important. The elements of forest production are:

marketplace — consumer
product producer — converter
raw material supply — grower/forest manager

For Canada, the marketplace is global, the products are also essentially global, that is, pulp, newsprint, and solid wood products to a lesser degree. The producers, with their major plants, are largely located for historical reasons in situations that may or may not be most appropriate for future production. One of the major factors has been and continues to be the existence of a natural supply of raw material — the forest. In the utilization and management of this existing growing stock a knowledge of climate and tree-growth relationships is largely academic. Albeit, in the matter of forest protection and fire management the application of meteorology is of crucial importance.

In many manufacturing industries, both the supply of raw material and even the converting or production plants can be moved and varied in relation to economic conditions. This flexibility is dominated by the global marketplace and hence international political and trade restrictions. Heavy industries such as steel have become prey to this globalization and we increasingly see it in forest products.

As forestry in Canada has been changing from a dominant exploitation of the natural forest to significant activities in forest renewal and intensive forestry, we have seen the application of 19th century professional forestry perspectives. The approaches have been based on managing for species/site selections. Understanding relationships between species and environmental factors within the context of existing management practices should enable us to manage our forests more efficiently and more effectively. Whether or not this ensures a raw material supply that gives future forest products an economic advantage in the global marketplace is a moot point.

Increasingly, for commodity products such as pulp and paper, as well as some "solid" wood products such as waferboard, the nature of the raw material and hence the species is of much less consequence than in the past. Increasingly in countries that we view as having highly developed silviculture along the conventional lines there is a move to greater uniformity in the raw material supply as part of a more comprehensive system. Three examples are well-known now — radiata pine in New Zealand, eucalyptus in Brazil and Chile, and lodgepole pine in Sweden. In all instances these production systems are essentially replacing indigenous forest species and are being used over a wider range of site conditions than the individual native species. This raw material supply is fueling the converting plants of Canada's competitors and this competition will continue and intensify. In terms of climate and forest production, what options lie ahead for Canadians? First, we have to assume that for the next few decades the overall climatic conditions will prevail, certainly for the major forest regions.

Second, we have to decide which species is going to provide our future raw material supply. In making such decisions a knowledge of climatic factors and factor/species relationships will be important. There is, in fact, an obvious analogy with agriculture. Given a quantifiable land base in a certain geographic location, from a knowledge of the existing and forecastable range in climatic conditions, it is possible to establish priorities for the growing of a range of species. For each species there will be some level of investment necessary for its production, indeed given a high enough investment, most plants can be grown in any location in the world. But the basic constraint is economic. The crop we are establishing can be justified only if it can be sold or converted to a marketable product at a profit.

The first level of species selection and application of a knowledge of climate is therefore at a small-scale level and usually has a few basic assumptions such as long-term projection concerning the nature of the raw material, availability of the land base, and usually the location of the converting plant. Once this decision about species has been made then larger scale relationships can be pursued and determined.

Let's consider a hypothetical example. A forest company producing market pulp from the existing natural forest utilizes various proportions of softwood and hardwood furnish. If the company believes that there will be a long-term market for that pulp it can either adopt a laissez-faire attitude and assume that the past represents the future, that is, it will continue to produce a product based on a raw material supply from a regenerated forest yielding roughly the same species mix as the existing forest. Given this situation one can forecast the silviculture principles and practices that will basically be employed.

First, the principle will be to regenerate existing desired species as effectively and efficiently as possible; the level will depend on availability of interest, expertise, and funds. There will also be some intensification to produce greater yields in selected areas. Sound familiar? In this scenario it is again forecastable that research into species/environmental factors will concentrate on soils and silviculture interrelationships with minimum studies of climatic factors, except as they are perceived to cause damage or marked growth differences.

What is the economic future of this company in the long run? Obviously no one knows but we can indulge in certain speculation and probabilities. I leave that to you.

Now let us consider that same company in the same location producing the same product. It rationalizes that any factor that can significantly reduce its cost of raw material will give it a competitive edge in the future. The existing natural forest is yielding 2.0 m^3 per ha per yr and the rotation age is 80–90 yr. Moderate increases in yield and on specific sites, even significant increases in yields, can be obtained by applying silviculture to the native species, but overall for the managed area this produces only a doubling of mean annual increment to 4.0 m^3 per ha per yr. However, competitive suppliers are already putting out market pulp based on yields of 9 m^3 per ha per yr and this may increase. The company in analyzing its position for the future can put forward an objective of a minimum of 10 m^3 per ha per yr from a certain area. Now we come to the implication of climate. What species can produce a uniform raw material supply over some defined range of sites that equals a specified productive rate; can efficiently convert solar energy; has a growth characteristic that makes it suitable for the defined site conditions; is capable of selecting and responding to a range of known silviculture practices; and, finally, although suitable for pulp can also be converted into other products if necessary?

That hypothetical example offers two scenarios that will result in different approaches and emphases in both management and research. These I leave to our ensuing discussion.

In concluding this paper, which is meant to stimulate discussion, I think there are some general characteristics of Canada's forest lands that are worth emphasizing as a productive base for forest products, compared with regions of lower latitudes where nominal growth rates may be much higher and from which we anticipate our greatest competition:

1. We have productive forest lands to an almost embarrassing extent and this tends to create a profligate attitude to their use, misuse, and "preservation." In fact, although not always in some persons' perceptions nor in all locations, we have considerable flexibility in terms of competing land uses and maintenance of diversity.

2. Climatically, our forest areas are subject to temperature and precipitation regimes that can provide for relatively high net primary production rates with minimal detrimental environmental consequences. Except on steep slopes and in certain very limited forest types and conditions, the maintenance of an adequate forest floor, and therefore conditions that minimize erosion yet provide significant nutrient pools, are readily maintained at little to no cost.

3. The forest industry of Canada is one of the world's largest. This is an asset in that a major infrastructure of converting plants is already in place. This is an asset only if it is maintained in a technologically efficient condition together with an economic supply of raw material.

These three factors of an extensive productive forest land base, climatic conditions that in effect buffer us from some of the most serious environmental damages, and a functioning infrastructure of converting plants should and can provide us with a confidence about our forestry future. But to ensure the future becomes a reality we will have to be critical in an analytical way to ensure we do not misapply our limited resources, professionally and scientifically.

HI-TECH APPLICATIONS IN OPERATIONAL FOREST CLIMATE MANAGEMENT

Session V. Hi-Tech Demonstration

Environmental Monitoring: Considerations of Integrating New Technology to Forestry

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Abstract

An increasing number of foresters are now able to obtain and install small, portable data acquisition systems. This presentation will give an overview of the main problems in using this technology. The specific categories of problems in the field and in the laboratory will be outlined. This information is a synthesis of the daily problems encountered in supplying and maintaining monitoring equipment with various climate clients throughout Canada. Regardless of the type of equipment used, there are still some basic problems associated with experimental design and the deployment of the equipment in the field. These range from human/machine interfacing to the lack of adequate sensors. Moreover, the choice of sensors and the frequency of data recovery and processing are not always done with standard techniques and guidelines. A brief overview of some of the available equipment will be described as shown in real time use.

Résumé

Un nombre croissant de forestiers peuvent maintenant obtenir et installer des petits systèmes portatifs d'acquisition des données. Cette présentation offre un aperçu des principaux problèmes liés à l'utilisation de la technologie pertinente ainsi que des catégories précises de difficultés qui surviennent sur le terrain et au laboratoire. Cette information est une synthèse des problèmes quotidiens liés à l'acquisition et à l'entretien de l'équipement de surveillance et auxquels sont confrontés divers clients du secteur de la climatologie partout au Canada.

Indépendamment du type d'équipement utilisé, il existe encore certains problèmes fondamentaux associés à la conception expérimentale et au déploiement du matériel sur le terrain. Ces problèmes varient de l'interfaçage homme/machine au manque de détecteurs adéquats. De plus, la sélection des détecteurs et la fréquence de récupération et du traitement des données ne sont pas toujours conformes aux techniques et aux lignes directrices normalisées. On présente un bref aperçu d'une partie de l'équipement existant ainsi que son utilisation en temps réel.

Introduction

The past decade of evolving technology has brought us an ever-expanding array of devices to monitor the environment. Whereas environmental monitoring used to be relegated to such specialized disciplines as meteorology, climatology, or hydrology, the capability and availability of monitoring are now widespread and increasing. In forestry, monitoring efforts were also usually relegated to meteorologists or hydrologists. Today, the many needs and applications of environmental measurements within forestry are varied: fire weather, nursery environments, reforestation, seedling establishment and growth, disease forecasting, spray applications, and water management, all require some form of description and understanding of the air and soil environment.

This presentation will deal with the problems associated with using the new technology. As a supplier of environmental monitoring equipment, we are involved with a wide range of disciplines and all of them have seen some variations of these problems. Forestry seems to be the one where these problems are more prevalent. It is not surprising since forestry is third behind the arctic and dirty industrial environments as the most difficult of operating conditions. Any equipment used within forestry must be rugged because of the difficult operating environments. Inevitably the demand for equipment that can be "thrown into the back of a truck or helicopter" has come from forestry. Furthermore, many forestry-monitoring programs are not operated year-round. The yearly installation and removal of the station tend to create more confusion and problems than in permanent or long-term situations. Forestry is also characterized by more nontechnical and seasonal staff, the people who will be operating the equipment. As a result, we also see a greater demand for equipment "simpler to use" from forestry.

Discussion

A general problem with the greater availability of the equipment is that practically anyone can now monitor the environment but few have the required background or training to do so correctly. The starting point in all of this is a most simple question: "Why measure?". This question can be easily answered and is always justifiable. The forester has already been required to answer this question simply, because of budgetary and/or managerial requirements. Sometimes the answer is simply "because we need to know when to plant" or "we need to know when to burn." A common yet valid reason for establishing a monitoring program is that the parameter (soil moisture, leaf wetness, or undercanopy radiation) or the area is not presently being measured by the regular climatic/meteorological network operated by Atmospheric Environment Service (A.E.S.). This is particularly true in forestry where the research sites and operation are usually remote. Translating these monitoring needs into a proper program is not as easily solved.

Another problem, although usually only found with first-time users of the equipment, is that the existing A.E.S. climatic database is usually ignored or not properly evaluated. An investigation of past climatic data from stations near or surrounding the proposed monitoring site will already give the researcher some idea of the variations that have occurred and an overview of the parameter's regime. Furthermore and perhaps more importantly, this preliminary review of existing information will give the researcher some familiarity with the type of information to be measured. Needless to say, the existing climate database will not necessarily have direct application to the proposed research. It will probably require extrapolation or further analysis.

Once a review of existing information has been done the researcher must then deal with more pertinent and immediate questions such as where, when, how many, and with what. Again we have found in dealing with clients that these questions are not always easily answered, especially when we attempt to identify the instrument requirements. The situation is further complicated by either the array of sensors to choose from or the complete lack of the required sensor. The new technology has not solved all monitoring requirements.

As with all scientific experiments, standards must be maintained. The forest researcher not only needs to meet these criteria, but also must be knowledgeable about the constraints of his own monitoring. The confusion between resolution and accuracy by some clients usually prompts us to question whether other criteria are being met. As with other disciplines, it is not always possible to satisfy both the monitoring standards and the research needs. The forester measuring wind speed near the ground cannot satisfy the 10-m height requirements. Furthermore, even with a second wind set because he/she wants to comply to a station network standard, the forester still cannot comply with the site location standards. At 10 m most forest canopies would cause interference. Creating the proper clearing is not always practical nor possible. A common example of lack of concern for standards is the monitoring of air temperature and humidity. In many situations we need to make our clients aware of the need for sheltering the sensor with a Stevenson Screen or equivalent radiation shield. Also, it is disturbing to discover how many clients who purchase humidity sensors do not own, or even know of, a proper psychrometer.

Standards need to be maintained for many reasons: the parameter must be properly measured and other researchers wishing to use the data need to know they can rely on the data. Furthermore, anyone establishing a new station should always consider the possibility that others will want the data or that an agency such as A.E.S. would want the station incorporated into their network. In terms of meteorological/climatological parameters the absolute authority remains the World Meteorological Organization (W.M.O.) (Anon. 1983, Anon. 1976); however, the availability and understanding of these documents can be difficult. Beyond the W.M.O., the authority in Canada is A.E.S. Yet A.E.S. itself is not prepared to answer these questions since it is also dealing with the changing technology.

A further characteristic commonly found with new users of the equipment is the tendency to not spend enough time becoming familiar with the instrumentation. An axiom of this is to also believe the monitored data without questioning it with a proper calibration. It is also disturbing to find that many monitoring programs do not have proper calibration techniques or schedules established.

Another problem stemming from the new equipment is the natural tendency for the user to overmonitor. This situation usually comes to light when the user faces an overwhelming mountain of data. Our dataloggers can sample fairly frequently (seconds) but can output processed data over longer time spans (hourly or daily). However, we still find clients with 5- or 15-min databases over several seasons. Apart from learning about monitoring, the forester first using dataloggers also discovers the need to learn computer programing, or worse, finds the computer support services to be inadequate. Even a few simple climatic databases from a few sites can quickly require a lot of computer storage and handling capability.

The second category of problems is related to the incorporation of this new technology within the general research environment and the associated human-machine interface problems. The keyword here is "user friendly." Whether we are discussing data acquisition systems, pocket calculators, or digital watches, there are always difficulties in explaining a new device. Everyone wants something that is easy to use and to understand. On the other hand, there are more requirements, types of measurements, and processing that researchers want. The two needs seem contradictory. Although we now have instruments capable of accomplishing many tasks, it is a different matter to also make the device user friendly. Our manuals have been praised as being good "measurement textbooks"; we are also quite aware that the simplification of documentation is still required. An alternative to expanding and simplifying our documentation is to make the datalogger's complex operation transparent to the user. This is now possible, but it is not a universal solution and does not eliminate the need for simpler manuals.

In forestry, as previously mentioned, part of the problem is that the technical support staff or field assistants are not familiar with this field or the equipment. There are two solutions to this. One is to properly train the field staff in the operation of the equipment; the other is to make the operation and the equipment totally transparent to the field staff and train them in a minimal fashion (i.e., learn how to change tapes or memory modules or perform some type of data transfer). We have found this second solution to be inadequate. The forester has spent a lot of money and effort in establishing a monitoring program. Field personnel must know how to properly maintain the equipment to protect this investment. Not only must they be able to retrieve data but they should have enough knowledge to evaluate whether or not the system and the sensors are operational. The worst example of this is when the field personnel are sent at great expense to isolated field sites and yet are not capable of properly assessing the status of all parameters being measured. "We don't want people pushing the wrong buttons" has been a familiar statement to foresters dealing with this situation. This no longer need be a concern since our dataloggers can now be password protected. Only the necessary instructions for station verification can be accessed and the programing left intact.

Other solutions to all these problems have been evolving as we have recognized them. In dealing with clients new to the field we now know to outline the main guidelines and the standards of a monitoring program. We have reached a situation with our equipment where it can perform complex measurements and yet still remain flexible and simple to use. For standard monitoring programs or network situations, we can burn the user's program into an EPROM (Erasable Programmeable Read Only Memory). This means that the datalogger need only be turned on in the field and the sensors properly connected. Common application of this feature within forestry, apart from dealing with untrained personnel, is to burn in the Fire Weather Index or a simple Evaporation-Water Demand Model.

To further eliminate the problems, we have developed three software packages. The first, called EDLOG, allows the user to write the datalogger program in his computer. At its simplest, EDLOG gives the user the means of properly documenting the program and keeping a record of it. The program can also be downloaded and uploaded to and from the datalogger directly, via cassette or through whatever telecommunications link exists. The next software package (TELCOM, TERM) is meant for researchers dealing with real time data and therefore using a telecommunications link. We are finding this to be more in demand as foresters set up data networks linked by either telephone, radio, hardwire, or combinations of these elements. The software allows for either automatic (TELCOM) or manual (TERM) polling of the stations. Apart from retrieval of the data, programs can be uploaded or downloaded. Furthermore, user-selectable parameters can be monitored in real time on the computer screen. The most popular software package is the SPLIT program. SPLIT helps the user break down the datafiles, perform further calculations, process them, and generate reports as well as send the data to a graphics routine.

Lower costs and simplification of use of the equipment should lead foresters to consider converting some of their sites from seasonal to year-round basis. The greatest costs have been met and operating the site over a longer period will spread the research effort further. Although the full year of data may not be as important to the forester, it certainly makes the station a better candidate for the Canadian network. This is especially true for remote sites.

Finally, with all the monitoring programs within forestry and the ensuing mounds of data, researchers should think of making their databases more accessible to others. A first step is to have a proper data catalogue. Once again, the more uses of the data, the better the return on the research investments. As more foresters establish networks with real time features, they will also have to consider the possibilities of other users gaining access to their network. Instead of worrying about data security, the forester should consider increasing the monitoring or modifying the programing so that other researchers could make better use of the data.

In conclusion, I propose that today's technology can solve many of the monitoring needs of the forester. There is still a need for better sensors for some measurements and the human operational side still needs attention. As we solve these problems, the forester can leave behind these monitoring considerations and concentrate more on the research problem at hand.

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Automation of Snow Measurements

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Abstract

At Canadian observing stations operated by the Atmospheric Environment Service (AES) and its cooperators, approximately 95% of the winter precipitation measurements are based on nonrecording, manual techniques of observation. The increased demand for automatic data acquisition, particularly in hydrology, agriculture, and forestry, will require new methods of snowfall measurements to replace the standard nonrecording methods. This workshop demonstration will review some of the impacts, opportunities, and options for automation of snow measurement, emphasizing the work being conducted by the Hydrometeorology and Marine Division of AES. A large Nipher-type shield has been developed for use on recording precipitation gauges to provide measurements that are compatible with the official MSC Nipher shielded snow gauge. Also, an ultrasonic snow depth sensor has been developed for use at automatic stations. This sensor used in conjunction with a recording precipitation gauge can effectively determine amount and type of precipitation at unmanned sites, and also can indicate the state of the snowpack.

Résumé

Aux stations canadiennes d'observation exploitées par le Service de l'environnement atmosphérique (SEA) et ses collaborateurs, environ 95 % des mesures de précipitations hivernales sont obtenues par des méthodes manuelles de relevé sans enregistrement. La demande accrue d'une acquisition automatique de données, particulièrement en hydrologie, en agriculture et en exploitation forestière, nécessitera l'emploi de nouvelles méthodes de mesures des chutes de neige pour remplacer les techniques traditionnelles sans enregistrement.

Cette démonstration en atelier examine certains des impacts, des possibilités et des options dans le secteur de l'automatisation des mesures des chutes de neige, avec une insistance particulière sur les travaux actuellement effectués par la Division de l'hydrométéorologie et de la climatologie du SEA. Un écran de grande taille, de type Nipher, a été mis au point à des fins d'utilisation avec un pluviomètre enregistreur qui doit fournir des données compatibles avec le nivomètre à écran de Nipher. De plus, on a mis au point un détecteur de la hauteur de la neige par ultrasons, qui doit être employé dans les stations automatiques. Ce détecteur, utilisé avec un pluviomètre, peut déterminer efficacement la quantité et le type de précipitations aux stations sans personnel et fournir également une indication de l'état du stock nival.

Assessing Moisture Status in Tree Nurseries and Forest Plantations Using the Pressure Chamber

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Abstract

The pressure chamber is a compact, durable instrument which provides a rapid measure of the moisture status of trees. To make a measurement a portion of the shoot (or root) is sealed inside the chamber with the cut end of the shoot protruding through a rubber seal. Sap will exude from the cut end of the shoot when chamber pressure equals the tension at which water is held in the plant. This pressure, termed plant moisture stress (PMS), indicates the moisture status of the tree. PMS is useful for monitoring moisture status of tree seedlings in nurseries and plantations. However, critical levels of PMS affecting seedling growth and survival have not been documented. One means of determining critical PMS is to identify the "physiological wilting point," using the pressure chamber to construct a pressure–volume (p–v) curve. The p–v curve is constructed by measuring PMS over a range of water contents. A computerized data acquisition program, suitable for nursery use, has been developed at the Ontario Tree Improvement and Forest Biomass Institute.

Résumé

La chambre de pression est un instrument compact et durable qui permet de mesurer rapidement le degré d'humidité des arbres. Pour effectuer une mesure, on place dans la chambre hermétique une portion de la pousse (ou de la racine) dont le bout coupé émerge à travers une fermeture étanche en caoutchouc. La sève sort du bout coupé de la pousse lorsque la pression de la chambre est égale à la tension à laquelle l'eau est retenue dans la plante. Cette pression, appelée «stress hydrique végétal» (SHV), indique le degré d'humidité de l'arbre. Le SHV sert à surveiller le degré d'humidité des jeunes semis d'arbres de pépinières et de plantations. Cependant, les niveaux critiques de SHV qui ont un effet sur la croissance et la survie des jeunes plants n'ont pas encore été étudiés. L'un des moyens de déterminer le niveau critique de SHV consiste à déterminer le «point de flétrissement physiologique» au moyen de la chambre de pression afin de construire une courbe pression–volume (p–v). Cette courbe est obtenue en mesurant le SHV en fonction d'une gamme étendue de teneurs en eau. L'Institut ontarien d'amélioration des arbres et de la biomasse forestière a mis au point un programme informatisé d'acquisition de données que les pépinières peuvent utiliser.

Introduction

The water status of trees is a reflection of the balance between water uptake from the soil by roots and water loss by transpiration from the foliage. When loss exceeds uptake, there is a net loss of water from the system, with a consequent increase in tree moisture stress.

Pressure Chamber

There are several methods for assessing moisture stress, but at present the most practical for forestry purposes is the pressure chamber (Ritchie and Hinckley 1975, Cleary and Zaerr 1980). It is a compact, durable instrument which provides a rapid measure of tree moisture status. This instrument consists of three basic components: a high pressure vessel, a pressure gauge, and a compressed gas cylinder. To make a measurement, a portion of a tree (usually the shoot) is excised and sealed inside the high pressure vessel with the cut end protruding to the atmosphere through a rubber seal. Pressure inside the chamber is slowly increased, at rates usually not exceeding 0.07 MPa sec^{-1} (Joly 1985).

The pressure at which sap begins to exude from the exposed cut end of the shoot equals the tension at which water is held in the plant. It usually takes only 1–2 min to make a single determination of moisture stress using the pressure chamber.

Interpreting the Physiological Significance of Plant Moisture Stress

Plant moisture stress is a measure of the chemical potential of water averaged for all living tissues in the plant. It is usual to express water potential in negative units, with fully hydrated plants having a water potential of 0, and increasingly negative values as water content declines. For operational field use, however, plant moisture stress may be expressed in positive units of pressure (Day et al. 1985).

Water moves in a tree along gradients of increasing plant moisture stress. For example, a transpiring tree needle will have a greater moisture stress than a root on the same tree in moist soil. As a result, water flows from the root to the shoot. The physiological significance of increasing moisture stress is, however, not obvious, since the transfer of water within a plant does not per se directly affect plant cell function. The significance of plant moisture stress can be interpreted, however, by expressing it in terms of its primary components, osmotic potential, and turgor potential. Plant moisture stress can be expressed as:

$$\psi pms = \psi\pi + \psi p \qquad (1)$$

where ψpms = plant moisture stress (i.e., water potential)

$\psi\pi$ = osmotic potential

and ψp = turgor potential

Osmotic potential is less (more negative) when the sap of living cells is more concentrated. A decrease in osmotic potential occurs either as a result of the production of more solutes in the cell (e.g. starch hydrolysis into sugars) or by a reduction in water content concentrating the existing cell solutes.

Turgor potential is the force of water pushing outward on the enclosing cell wall. Turgor potential increases when water of low solute content from the xylem enters the cell by osmosis to equilibrate with the solute-rich cell sap. As cell water content increases there is a physical push outward which is resisted by the cell wall. Water continues to enter the cell until the force of the cell wall resisting the push of water is equal (and opposite) to the osmotic potential. Thus, turgor potential cannot exceed the magnitude of osmotic potential.

Unlike plant moisture stress, both osmotic potential and turgor potential have direct plant cell physiological importance. Changes in osmotic potential affect rates of metabolic activity by altering concentrations of metabolic substrates and end-products (Tyree and Hammel 1972, Leopold and Kriedemann 1975). Osmotic potential is also important because it determines the maximum turgor potential that can be reached. The pressure produced by turgor potential is the driving force for cell enlargement (Cosgrove 1986, Van Volkenburgh and Cleland 1986). In addition, turgor potential has a controlling role in many physiological processes (Hsiao et al. 1976, Levitt 1980).

Problems in Interpreting Plant Moisture Stress

There is at present no guide based on physiological principles by which to judge whether or not a damaging plant moisture stress has been reached. Plant moisture stress indicates the degree of water stress in a seedling, but does not necessarily indicate whether the stress was damaging. In addition, the ability of trees to tolerate high moisture stress levels varies seasonally (Mullin 1967, Colombo 1987), so that a single plant moisture stress value could not be used as a critical value for both actively growing trees and trees in a state of winter dormancy.

Requirements for Operational Use of Pressure Chamber

For forestry purposes, an operational procedure using the pressure chamber should meet the following prerequisites:

(1) Pressure chamber readings should be interpretable into values with physiological importance.

(2) The procedure should sample a representative proportion of the tree population.

(3) Seasonal and culturally induced changes in drought tolerance must be accounted for in the procedure.

The Wilting Point as a Measure of Critical Plant Moisture Stress

We are proposing that the wilting point (i.e. the point at which turgor potential, ψp, first equals 0), be used as a critical value of plant moisture stress (Colombo 1984, Colombo et al. 1984). In actively growing seedlings, the wilting point is visible as a physical loss of turgor. Even woody stems, however, "wilt," although it is a physiological rather than a physical wilting.

The physiological wilting point can be determined using the pressure chamber, by graphing the relation between reciprocal plant moisture stress and relative water content,[1] known as a pressure-volume (p-v) curve. A typical p-v curve is shown in Figure 1. An important feature of p-v curves is that there are two distinct regions of the graph: a curvilinear decline in reciprocal plant moisture stress with decreasing RWC, followed by a region of linear decline in reciprocal plant moisture stress and RWC. The point at which the curvilinear and linear regions meet is the wilting point. The wilting point meets our three criteria for operational use.

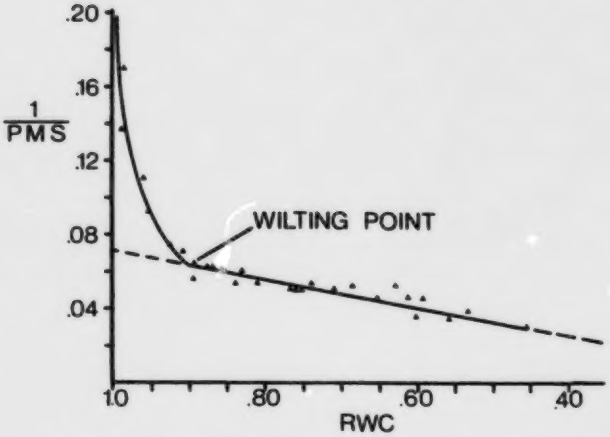

FIG. 1. A typical pressure-volume (p-v) curve, showing the relationship between reciprocal plant moisture stress (PMS) and relative water content (RWC).

(1) Pressure chamber readings are interpretable into values with physiological importance.

At the wilting point, turgor potential first reaches zero. At zero turgor, the measurement made with a pressure chamber is a direct reading of osmotic potential, since, as given in equation (1), $\psi pms = \psi\pi + \psi p$. Thus, when $\psi p = 0$, $\psi pms = \psi\pi$. The physiological significance of the wilting point is that it is a measure of turgor pressure, and turgor pressure is related to cell growth (Cosgrove 1986) and stomatal closure (Hinckley et al. 1983).

(2) The procedure samples a representative proportion of the tree population.

We have modified the p-v method to sample a minimum of 15 shoots for each p-v curve (Colombo 1984). The classical technique samples only one shoot (Tyree and Hammel 1972), while some revised techniques sample 5 or 6 shoots (Hinckley et al. 1980), which has until now been a principal limitation to operational application. In our experience, a p-v curve consisting of 15-20 shoots provides an adequate sample of a greenhouse or nursery compartment of seedlings. One operator using a single pressure chamber can construct up to 5 p-v curves at one time.

Once the "average" wilting point has been determined for a seedling stock lot, plant moisture stress can be measured using a sample of 10-20 seedlings (number depending on variability) at critical times during stock handling (e.g. at lifting, during shipping, and at planting) to determine whether the wilting point has been reached.

(3) Seasonal and culturally induced changes in drought resistance must be accounted for in the procedure.

The wilting point varies seasonally in black spruce from a minimum of 1.5 MPa during active shoot elongation to

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[1] Relative water content (RWC) $= \dfrac{\text{fresh weight - dry weight}}{\text{fully saturated weight - dry weight}}$

$$= \frac{\text{fresh water content}}{\text{water content at full saturation}}$$

a 3.0 MPa maximum during winter dormancy (Colombo 1987). Therefore, the p–v technique for determining the wilting point will be sensitive to seasonal and cultural changes in tolerance to plant moisture stress.

Computer-Assisted p–v Curve Data Acquisition

We have developed a procedure for constructing p–v curves using an Apple II+ microcomputer. This program calculates shoot weight loss and signals the operator to measure plant moisture stress at appropriate RWC's. For each p–v curve, up to 30 shoots, fully hydrated by water soaking overnight, are allowed to air-dry, and each shoot is sampled once during drying to determine plant moisture stress. From 5 to 30 tree p–v curves can be run simultaneously. The advantage to using this program is that the burden of arithmetic calculations of RWC is removed from the operator and is performed by computer. This should allow the operator to devote more attention to the accuracy of weight and plant moisture stress determinations. A report describing and documenting this p–v data acquisition program is in preparation.

Summary

The pressure chamber is a durable and field-portable instrument for measuring the plant moisture stress of trees in nurseries and plantations. It has great potential as one of the few available measures of tree physiological status. Using the pressure chamber, the wilting point can be determined and used as a critical moisture stress which trees should be prevented from reaching. This is an operationally acceptable method because the wilting point is a measure of physiological significance, provides samples of a representative proportion of the population, and varies seasonally and in response to cultural practices. A computer-assisted, p–v curve data acquisition program has been developed.

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Use of Intelligent Dataloggers for Climate-Irrigation Management in Seed Orchards

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Abstract

Forest managers from industry and government are investing in the development of genetically superior sources of seed and stock through tree improvement programs. Eleven black spruce (*Picea mariana* (Mill.) BSP) seed orchards and 22 black spruce genetic test areas have been established in northwestern Ontario to provide improved seed for regeneration programs. Tree seed orchards are deliberately located on deep, well-drained soils to take advantage of the moisture stress and enhance seed production. During the establishment phase, irrigation is required to ensure survival and vigor. The irrigation scheduling program is capable of operating within a relatively flexible management structure and provides field estimates of soil moisture status and irrigation requirements. Because of the remote location of seed orchards, this operational irrigation model is based on the Priestly-Taylor approach with specific atmospheric and soil qualifiers. Results are presented that illustrate the operational flexibility of this integrated scheduling and monitoring system plus site calibration procedures. The model currently operates on a hand-held intelligent datalogger, manufactured by DAP Industries, Quebec. This unit (CP/M based microcomputer with 128K) has been field-tested in the seed orchards for 2 yr and will be demonstrated.

Résumé

Les gestionnaires forestiers du secteur privé et du gouvernement misent actuellement sur la mise au point de sources génétiquement supérieures de semences et de matériel de reproduction par des programmes d'amélioration des arbres. 11 vergers à graines d'épinettes noires (*Picea mariana* (Mill.) B.S.P.) et 22 zones d'essais génétiques sur l'épinette noire ont été établis dans le nord-ouest de l'Ontario afin d'améliorer les semences pour les programmes de régénération. Les vergers à graines sont délibérément établis sur des sols profonds et bien drainés afin de tirer profit des conditions d'humidité et d'augmenter la production de semences. Au cours de la phase d'établissement, l'irrigation est nécessaire pour assurer la survie et la vigueur des plants. Le programme d'irrigation peut être exploité à l'intérieur d'une structure de gestion relativement souple et fournit des estimations sur le terrain de l'humidité du sol et des besoins en irrigation. En raison de l'éloignement des vergers à graines, ce modèle opérationnel d'irrigation est fondé sur l'approche Priestly-Taylor avec des qualificatifs précis de l'air et du sol. Les résultats présentés illustrent la flexibilité opérationnelle de ce système intégré de surveillance et de programme de l'irrigation ainsi que les méthodes d'étalonnage sur le terrain. Le modèle fonctionne actuellement avec un système informatique d'enregistrement chronologique des données, qu'on tient à la main, fabriqué par DAP Industries du Québec. On fera la démonstration de cet appareil (microordinateur basé sur le système d'exploitation pour micros 8 bits avec une capacité de 128K), mis à l'épreuve dans des vergers à graines pendant deux ans.

Introduction

The pulp and paper industry in Ontario requires a continuous supply of high quality black spruce (*Picea mariana* (Mill.) B.S.P.) timber. The Ontario Ministry of Natural Resources and several forest companies cooperate to ensure a future wood supply through careful harvesting, silviculture practices, and tree breeding. Tree breeding requires a planned and integrated process of tree selection, mating, and genetic testing to produce seed or source material for future generations. In return, this raises the probability of planting trees with accelerated growth rates with the desirable commercial characteristics.

Superior trees are selected from natural black spruce stands based on their growth rate relative to that of the surrounding trees. Seed is collected, germinated, then planted together in a seed orchard to interbreed and produce genetically superior seed. Within this seed orchard the trees are located to encourage random mating and restrict inbreeding among the families. Families that do not perform well in concurrent field tests are identified and removed to ensure that only superior performers remain in the seed production population.

Seed production is influenced by soil and climatic conditions and can be artificially enhanced with treatments such as fertilization, wire girdling, subsoiling, growth hormones (gibberellins), and root-pruning (Ross and Pharis 1981, Masters 1981, Schultz 1971). Natural moisture stress periods that are characteristic of well-drained soils are very effective for enhancing flower production and ultimately seed yields. The object is to incur moisture stress conditions at the time when buds differentiate into either vegetative or reproductive buds. Moisture stress conditions favor reproductive buds. At all other times, an adequate moisture supply is necessary to maintain tree vigor. For these reasons, as well as the ease of operational management, deep, well-drained sandy loams are recommended for seed orchard sites.

However, during the establishment phase of a seed orchard, adequate moisture is mandatory for survival and development of black spruce. In the seed orchards in northwestern Ontario, recurrent periods of soil moisture stress required the implementation of irrigation systems. Practical operational questions were immediately raised concerning when to "turn on the tap," "how long to leave the tap on," and "how much fertilizer to apply."

An operational tool that was sensitive to the daily atmospheric and soil moisture balances, but required minimal equipment and time, was needed to effectively regulate irrigation. Similarly, for fertilization, information on rates, composition, and timing of fertilizer was needed to optimize the balance of nutrients. To answer these questions, operational field trials for both irrigation with and without fertilization were statistically designed and implemented in a production seed orchard. The development of operational models for this orchard site were flexible in their designs to allow their application in other black spruce seed orchard locations. This paper identifies the integrated irrigation model and it's operational application with the aid of intelligent hand-held dataloggers, to effectively enhance the health of a seed orchard.

Study Site

The seed orchard is located on Goodie Lake, in Lomond Township, near Sioux Lookout, Ontario, at latitude 50° 07' N and longitude 91° 54' W. Generally, the area receives 712 mm of precipitation annually with a mean annual potential evapotranspiration of 528 mm. The mean annual temperature is 1.1°C and the mean length of growing season is 114 d. The soils are well-drained loamy sands, developed on glacial outwash.

This 5.2-ha site was root raked, disked, and mounded in the spring of 1982. Planting of 16 000 trees followed immediately, using both bare-root stock and container stock.

The orchard planting design is based on a compromise that optimizes several genetic concerns such as outcrossing, inbreeding, and spacing. A total of 320 families are grouped into four sets of 80 families with one tree from each family planted in each of 50 blocks. Randomly selected families are planted in 4-tree clusters around a center stake for a total of 20 clusters per set spaced 3 m between clusters. Based on the results of the genetic tests, the orchard will be thinned to 25% of the original 16 000 trees such that only 1 tree per cluster remains.

For the development, testing, and calibration of this integrated irrigation model, 30% of the production seed orchard was overlayed with a complete randomized block design and subjected to varying levels of irrigation and/or fertilization. Total height, annual height increment, and the health of each tree was also measured annually (from 1983) for biological calibration of the irrigation model coefficients.

Climate–Irrigation Model

To provide an estimate of the amount of water required by the seed orchard stock, an irrigation scheduling model was developed using climate data and the available irrigation system. Irrigated water is provided by a diesel-powered, mobile pump and wheel-mounted volume guns.

DATA REQUIREMENTS

Operation of the irrigation system, once the model is calibrated for a particular site, requires daily values of temperature (maximum and minimum), relative humidity (maximum and minimum), and total rainfall plus hourly observations of solar radiation.

Various methods are available for observing and/or recording these parameters. These include electronic dataloggers, mechanical recording strip-chart devices (e.g., hygrothermograph), and traditional climatic instrumentation such as the maximum/minimum thermometer. The remoteness of this seed orchard site and the available financial and human resources limited the instruments to a combination of mechanical recording and traditional instruments. A 7-d recording format is more than necessary to allow flexibility in scheduling visits to the site under normal operating conditions. In addition, this type of equipment maintains a minimal capital investment at high-risk, unattended locations yet provides the required precision and parameters for the irrigation model.

The climatic equipment was located adjacent to the seed orchard in an area not directly affected by current seed orchard management practices (e.g., irrigation). The equipment includes a 7-d recording hygrothermograph which provides a continuous recording of temperature and relative humidity located in a standard Stevenson screen along with traditional maximum and minimum thermometers. These thermometer readings are essential to calibrate the hygrothermograph temperatures.

Rainfall is recorded using a tipping bucket rain gauge and chart recorder which provide a continuous trace indicating the amount and rate of rainfall in 1.0-mm increments. In addition, three standard AES type B rain gauges were located within the orchard, one in each of the three experimental plots. (For the purpose of the experiment, three levels of soil moisture status were prescribed and the site was divided into three equal area plots.) The rain gauges were used to measure the amount of irrigation water applied on a particular day.

Solar radiation is measured using a mechanical pyranometer. This device provides continuous recording of the solar radiation received on a horizontal surface. Hourly values are abstracted from the chart and used to calculate the total daily solar radiation.

The irrigation model requires, in addition to the daily climatic parameters, the previous days soil moisture status. This was initially obtained using a series of gravimetric samples taken on the start-up day in the spring. Samples are normally taken throughout the experimental plots to provide a representative value in each of the plots. Once the model is running, the soil moisture status is a regular output of the model and is continuously recorded and carried forward for the next day's calculations.

To facilitate translating the model output in terms of irrigation amount into an operationally useable value, the existing pump and irrigation system were calibrated. The pump pressure was noted when the distribution of irrigation water in the orchard minimized spray overlap conditions. This information, along with the manufacturer's calibration values relative to the spray heads plus test trials using the AES type B rain gauges as ground truth, allowed for the development of a relationship between the amount of irrigation water and equivalent units of time of operating the system at standard pump pressures. (For further information on this irrigation model see "Climate and Irrigation Scheduling in a Seed Orchard Environment," by R.B. Street, this issue.)

INTELLIGENT DATALOGGER OPERATIONS

The intelligent datalogger selected for this application was the Microflex by Dap Industries, Quebec City, Quebec, Canada (Fig. 1). This unit is a hand-held CP/M-based 128K microcomputer. The unit is completely sealed with nickel cadmium batteries rechargeable via an associated moducom

FIG. 1. The Microflex by Dap Industries, Quebec City, Quebec. This unit is a hand-held CP/M-based 128K microcomputer.

unit. In addition, this moducom serves as the RS 232 communication port and requires AC power. Because this unit is a CP/M microcomputer, it supports several third-party languages (MacIver et al. 1984, MacIver 1985 and 1986).

For the purpose of this integrated irrigation model the Microflex was especially appropriate having the mathematical capability to support the Priestly–Taylor irrigation model. Additional programing to provide range checks, error detection, alphabetic, and/or numeric data verification minimized error in remote field locations, especially with staff unfamiliar with the climatic-irrigation models.

The irrigation model was initially developed on an IBM microcomputer, then downloaded into the Microflex. Uploading of data files into either Digital or IBM microcomputers (depending on the microcomputer support in local district office locations) for further data analysis or archiving is possible.

The software program is user-friendly and queries the operator for basic calendar and recorded climatic parameters at the seed orchard location. The input values are daily maximum and minimum temperatures, relative humidity, total rainfall, and hourly solar radiation. The outputs generated by the irrigation model identify and record the soil moisture status at the end of the day and the amount of irrigated water needed. This latter parameter, given the specific characteristics of the irrigation system (e.g., psi), is converted by the microcomputer program and provided in terms of the time required to "turn on the tap."

In addition, the Microflex provides the capability to irrigate plots at varying levels, subject to different soil moisture thresholds. Also, by using the recorded climatic data and outputs of the irrigation model, it is possible to continuously monitor the soil moisture status in either graphical or tabular form. This has proved rewarding for determining the frequency of visits to the seed orchard to irrigate. For example, during periods when the soil moisture is high, visits were limited to once or twice a week, especially when the probability of precipitation was also high. More frequent visits were required during moisture stress periods. The lead time provided by the climatic-irrigation model forecasts allowed the scheduling personnel needs and improved irrigation applications at these remote seed orchard locations.

This same monitoring of soil moisture station via a climatic-based irrigation model has direct application at provincial tree nurseries with similar improvement in irrigated water applications and cost-saving through scheduling personnel and equipment.

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Physio-Climate Detection and Modeling with the Computerized Tree Ring Increment Measuring (TRIM) System

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Abstract

Physiological growth and development profiles of individual trees and unit area plots will be demonstrated with the Ministry of Natural Resources Tree Ring Increment Measuring (TRIM) System. In addition, climatograms by soil type provide interpretative support for the analytical growth layer procedures. Current mathematical models fail to include the climatic causative factors that influence temporal and spatial tree growth patterns. Physio-climate mathematical frameworks are suggested.

Résumé

Les profils de développement et de croissance physiologiques d'arbres individuels et de placettes de superficie unitaire seront démontrés à l'aide du système de dendrométrie (TRIM) du ministère des Richesses naturelles. De plus, les climogrammes par type de sol facilitent l'interprétation des résultats de l'analyse des couches d'accroissement. Les modèles mathématiques existants n'intègrent pas les facteurs climatiques qui déterminent les configurations de croissance temporelle et spatiale des arbres. Cet exposé propose des structures mathématiques de physioclimat.

Introduction

Analytical models depend on both the availability of data and its precision. The first ingredient is not a problem in forestry but when combined with the second ingredient becomes serious and limiting. The greater the vertical translation of data to information to knowledge then the greater becomes the need for highly iterative and precision critical analysis. To a large extent the forestry knowledge pyramid is dominated by the lower level of mechanistic clerical processing of data commonly called "computer chunking." Translation of these data to knowledge is, for example, a function of statistics assuming that the basic conditions for the realization of this knowledge are inherent in the origins of the data. With the widespread introduction of computers, especially microcomputers, forest management is facing an explosion of the traditional data matrix. Some of these data will contain relevant "information," yet much of the data has no relevance to areas and topics they attempt to measure. Simply stated, management must continue to focus on the biological, not the electronic tree.

To overcome this deficiency within the multidisciplinary framework of forest growth and development led to the development of a Computerized Tree Ring Increment Measuring (TRIM) System (Fayle and MacIver 1986).

The patterns of successive changes in width and length of the annual growth layer of stem wood during the life of a tree integrate much of its history, particularly climate. To identify external perturbations compared to the "normal" biological patterns of growth and development requires an understanding of the dynamic, not the static, processes of forest development. Critical to this goal is the sectioning of all trees at sufficiently close intervals within their respective forest community by unit area to document the detailed radial and longitudinal patterns of growth. In all cases, the growth layer is the basic unit of measure.

Tree Ring Increment Measuring (TRIM) System

Until the advent of the microcomputer, growth layer analysis was too time-consuming and expensive for all but research studies. Currently 26 TRIM Systems are in service in research and management applications in Canada and the United States. Twelve of these systems are in daily operational use (some double-shift operations) within the Ontario Ministry of Natural Resources by field management staff, to obtain information on physiological tree and stand growth.

TRIM is a computerized growth layer analysis system assembled largely from off-the-shelf parts. It is not tied to the mainframe computer; it is rugged, easy to use, and precise. The system consists of two parts — hardware (Fig. 1) and software elements. The following description is from Fayle and MacIver (1986):

"The custom designed measuring table (engineering diagrams available upon request) can be constructed at a local machine shop. All metal components are precision tooled and pressure relieved to maintain continuous accuracy over the 550 mm linear-bearing travel distance of the measuring platform. A screw drive, turned by a geared hand crank, incorporates a split-nut construction, allowing rapid horizontal transfer of the measuring platform. Movement of this 34x34 cm platform is detected by a Sony Linear magnescale mounted in the measuring table and capable of reading at a precision of 0.01 or 0.001 mm. Cumulative distance travelled is displayed on the accompanying Sony Controller unit. Transfer of data is via the RS 232 port of the controller to the microcomputer.

Individual ring width measurements are initiated by the TRIM Operator pressing a button as the microscope crosshairs intersect the ring boundary on the tree disk. This in turn transmits an interrupt signal to the microcomputer. The software calculates the difference between these cumulative distance signals and displays the ring widths, identified by year, on the monitor for immediate error-checking. Once a complete radius is measured, the ring width sequence is graphically displayed on the monitor along with the previous sequence for verification by the operator. If errors are detected, interactive editing of the data is readily available. Raw data are stored on one disk drive and average data of several radii on the other.

The TRIM software was developed as a set of interactive menu-driven programs specifically aimed at the casual user. This has proven to be operationally attractive in remote field locations where specialized computer operators may not be

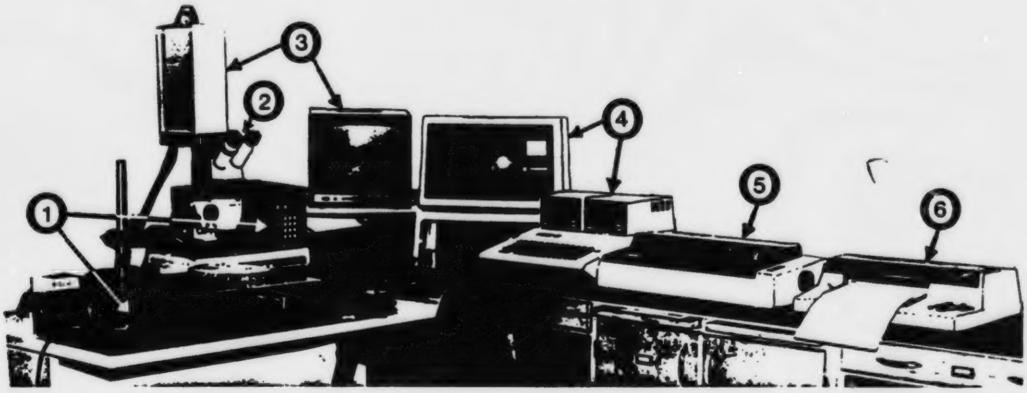

FIG. 1. TRIM System showing (1) measuring table and Sony controller; (2) stereomicroscope; (3) TV camera and monitor; (4) Apple IIe microcomputer, dual disk drives and monitor; (5)132-column Epson FX-100 printer; and (6) Hewlett-Packard 6-pen.

available. Numerous programs with detailed instruction manuals (14) have been developed. Standard tabular and graphical outputs include growth layer profiles and stem profiles for width and cross sectional area, annual and cumulative height, cumulative volume, CAIV/MAIV, specific volume increment and radial sequences. Aggregation software allows the user to aggregate all trees in a plot or to selectively stratify and aggregate individual trees by class interval: height, age, dbh, crown width, crown length. Stocking and density stratification is possible from our polar plot or rectangular plot mapping software. In addition, field sampling, ring identification and registration manuals have also been developed."

Sampling Designs

In most forestry projects, randomness is assumed. Specifically for new plantations, the assumption of regularity is sometimes recognized before the analysis; in others, the assumption of regularity is disregarded and randomness is assumed to govern the probabilities. The nature of the sampling distribution in which probabilities are assigned to the outcomes are critical to the current TRIM sampling methodologies.

The distribution of trees by unit area and their ability to change over time necessitates unit area mapping of all species (Fig. 2). This mapping technology is common to all TRIM procedures. Traditionally in forestry, only the commercial tree species are tagged and remeasured, whereas the spatial distribution of these crop trees with the location of their intraspecific competition is ignored.

Generally, spatial distribution patterns at any point in time can be classified as either uniform, random, or clustered. However, sampling probabilities are sensitive to the manner in which trees occupy their respective space. This can be easily demonstrated by changing the quadrat sizes and a different frequency distribution will result, especially in clustered stands.

Both the old forest and, in many cases, the new forest commonly exhibit clustered spatial distributions. In these cases, traditional density/stocking parameters are poor measures of the spatial distributions of trees by unit area. Consequently, spacing indices derived from unit area mapping of all species are critical ingredients for productivity forecasting.

In recognition of these spatial distribution patterns, a minimum sampling design was developed in which four randomly located 20x20 m plots with an inner 10x10 m destructively sampled area are established per forest stand. In all cases, all species within the 20x20 m area are mapped (Fig. 2). From this data base, species-spacing indices have been calculated by comparing the cumulative percent of trees with the cumulative percent of area occupied.

Physio-climate detection depends not only on the aggregation of individual trees by unit area into stand levels of performance, but also on the within tree sampling intensity. The biological growth information is stored with the tree. To unravel this physiological data base requires a sampling design that is sensitive to changes in environmental site and stand structure influences. For example, the within tree sampling intensity for jack pine (*Pinus banksiana* Lamb.) is:

Disk Interval	Within Tree Sampling Locations
15 cm	Within 2 m of the apex
45 cm	165 cm to a point 2 m from apex
15 cm	Base to 120 cm

In addition, a disk is also taken at the diameter at breast height, (D.B.H.) and base of live crown (B.L.C.). In other species where the internode height can be confidently located in the field, the within tree sampling intensity is adjusted accordingly, for example, hybrid poplar.

For the purpose of growth layer analysis, the within disk sampling was standardized as the north–south radii. In all cases, a minimum of two radii are measured with additional cardinal radius measurements taken where the tree disk is highly eccentric about the pith.

The selection of these two radii was derived from the CAIV/MAIV comparison of all possible combinations of four cardinal radius measurements plus the average radius compared against the digitized cross-sectional area contained

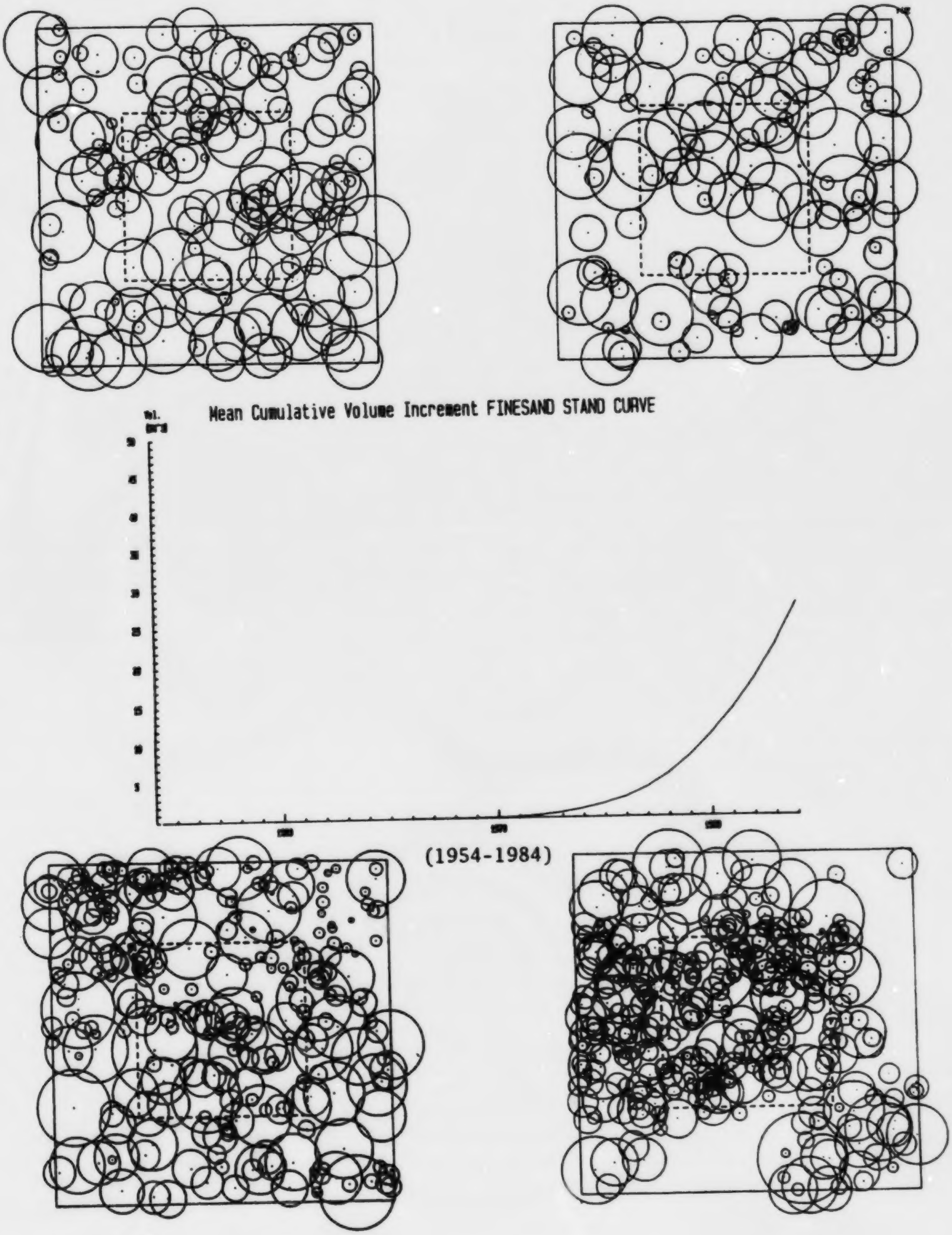

FIG. 2. Graphical representation of minimum sampling design, in which four randomly located 20 x 20 m plots, with an inner 10 x 10 m destructively sampled area, are aggregated to produce a mean cumulative volume increment curve for the forest stand.

within each annual growth ring for individual jack pine, black spruce (*Picea mariana* (Mill.) B.S.P.), and white spruce (*Picea glauca* (Moench) Voss) trees. It is, however, recommended that where budgets are not limiting that four cardinal radii be taken per disk section. Conversely, one radius is not sufficient, especially for physio-climate analysis.

Having now established a TRIM data base by unit area for all trees, numerous software programs and manuals have been developed for the Apple IIe microcomputer. For example, each module allows the user to interactively select individual trees within the unit area plots/stands with aggregation by years at the plot/stand/forest performances levels (Fig. 2). In all cases, final report generation is either in tabular or graphical form.

Modeling Stand Growth and Mortality

Mathematicians tend to regard the simplest equation as the most elegant, probably because simple equations often can adequately explain the outcome of numerical, physical, and chemical phenomena. Simple, elegant equations may even prove adequate for such things as microbial population growth under laboratory conditions that are tightly controlled by the experimenter. However, simple equations, even when aggregated into models will rarely be adequate to explain or predict biological growth in nature's vast laboratory. State-of-the-art models of growth and mortality in forest stands employ such relatively simple equations that they can express only highly smoothed, long-term trends in growth and mortality rates over time.

Smith and Hann (1984) made a major step forward in mathematical modeling by publishing a family of equations, each of which related trends in mean values for volume or basal area, or in quadratic mean diameter, to survivorship in tended, self-thinning stands of red pine (*Pinus resinosa* Ait.). More recently, Smith and Hann (1986) using a complex set of mathematical procedures, involving 10 equations and several assumptions about height–age relationships, to convert one of their original equations into a model for mortality and volume growth in red pine.

Comparable results for trends in mortality, volume, and basal area growth were obtained more directly from much of the same data. This was accomplished by using a very slightly modified version of one of the Smith–Hann (1984) equations relating survivorship to both basal areas and gross total volumes and by adding a second equation for basal area increment as a function of basal area, age, and site index at age 50. This second equation was one used by Leary and Florey (1982) in their programable calculator model for thinning red pine stands. Fitting was done for both basal area and gross total volume. The equation used for both of the survival–size relationships was:

$$\bar{Y}_{ij} = b_1 - b_2 \bullet X_{ij1} - (b_3 - b_4 \bullet X_{0j2} - b_7 \bullet X_{0j4}) \bullet e^{-b_5 \bullet X_{ij3}^{b_6}} \qquad (1)$$

where $\bar{Y}_{ij}$ is the log of either mean basal area or mean volume, i is the number of remeasurement dates, j is the number of initial spacing levels, X_{ij1} is the log of the frequency, X_{0j2} is the log of the $0_{j\text{-th}}$ or first-observed frequency, X_{ij3} is the log of the ratio of the $0_{j\text{-th}}$ frequency to the ij-th frequency, and X_{0j4} is the log of the first-observed mean basal area. Modification consisted of adding the term "$-b_7 \bullet X_{0j4}$" in an attempt to ensure maximum correspondence between the two relationships.

TABLE 1. Coefficients for equations (1) and (2) used in the red pine and jack pine models.

Coefficient	Red pine equations (1)BA	(1)VOL	(2)
b_1	4.75828900	9.48929020	6.05771930
b_2	1.04644490	1.33053700	1.12262680
b_3	1.62122780	3.70644050	0.000015691153
b_4	0.24209815	0.56701014	0.84425814
b_5	2.28935770	0.20125000	0.17435975
b_6	0.34215973	0.31140694	3.82657670
b_7	0.37733967	0.85623949	

Coefficient	Jack pine equations (1)BA	(1)VOL	(2)
b_1	2.97708930	10.154947000	4.24075450
b_2	0.92064789	1.702192200	0.81307240
b_3	1.04420750	9.647880900	0.26035925
b_4	0.61842321	2.046193200	0.86278297
b_5	0.48862227	0.075431979	0.62815229
b_6	1.11075320	3.517604700	2.46610298
b_7	0.87113029	1.379446900	

Next, those two fittings were expanded into a growth and mortality model by using a second equation predicting basal area increment from age, site index, and basal area, namely:

$$\text{BA growth} = b_1 \bullet \text{Age}^{-b_2} \bullet \text{BA} - b_3 \bullet \text{Age}^{-b_4} \bullet \text{SI}^{-b_5} \bullet \text{BA}^{b_6} \qquad (2)$$

where BA is basal area and SI is site index at 50 yr after planting.

Later, the two equations were also fitted to the combined three site classes for jack pine (*P. banksiana* Lamb.) provided by Plonski (1974) in his Metric Yield Tables. Fitting the jack pine indicated that the appropriate site study values for those classes were 19.9, 16.9, and 14.0, respectively, in this application. The results were fairly satisfactory except that when site Class 1 was modeled, mortality caused the growth to become negative after the 60th yr. The coefficients obtained by fitting (1) for basal area and volume and (2) are given in Table 1 for both species.

Using those coefficients, insert into (2) the site index value, the number of years between planting and the first observation, the survivor frequency, and the basal area at that time. This will generate the basal area 5 yr later. Insert this new basal area value into the basal area version of (1) to get the new frequency. Next, insert the new frequency into the volume version of (1) to give the new volume. Then repeat the process until the new basal area or volume values begin to decrease.

However, neither the Smith–Hann (1986) model nor ours adequately explains or predicts stand growth and mortality. Neither model contains parameters dealing with the highly influential impacts of year to year fluctuations in climate on the trends in growth and on the mortality rates.

For example, one of the earliest impacts of climate on growth is that it can prolong the "establishment period" which often occurs between the time transplant stock is planted and the time it begins to grow at an expected rate. Some sampled white spruce plantations have experienced establishment periods of 6-8 yr with many of the trees exhibiting frost rings for most of those years.

Once trees leave the establishment period, they tend to grow rapidly but at annual rates which tend to diminish each year. This decrease in the rates appears to be related to the increasing competitional stresses consistent with the increasing size of the trees. Annual fluctuations in the favorability of climatic years influence the annual growth rates. Periods of "thermal stress" (MacIver 1988) certainly lower the annual rates. However, the most dramatic impacts of climate on growth and mortality happen when such periods occur consistent with the strengthening competitional stresses which cause the stand to approach stagnation. The accumulative interactions of those stresses reduce growth abruptly and result in the mortality of some trees while predisposing others to die later. Aperiodic "bursts" of mortality are commonly observed in shade-intolerant conifers such as jack pine.

When thermal stress periods are replaced by more favorable climatic years, growth rates in most surviving trees tend to recover. Sometimes, especially on "prime sites" these recovering rates can temporarily exceed those that predated the onset of the stress period.

It should be clear from the foregoing why and how we must change growth and mortality models driven by age. Instead of starting the growth clock as soon as a stand is cut, the analysis must wait through any delay period there may be between cutting and replanting, as well as through any establishment period, before growth increments are compared.

Also, models must be made to be reactive to actual climate. Growth and mortality predictions obtained from any stand growth model assume that the climate for the prediction period will average out about the same as what occurred during the period(s) from which the model was derived. To compensate for this necessary but often unrealistic assumption, we must cause the model to accept the actual climatic information that occurs, to adjust its rates according to annual fluctuations, and to reset its growth clock as periods of thermal stress come and go.

We now have an equation that appears capable of determining the manner in which changes of trends in growth rates have occurred during the development of each dimension of any stem bole described by the application of TRIM procedures. It appears to apply equally well to either conifers or hardwoods and to indicate when any given stem's neighbors have died. If those apparent benefits can be confirmed and appropriately evaluated, this equation should become the core of a truly dynamic model capable of responding to competitional and climatic stresses.

Note: Computer programs can be obtained by writing to the authors: D.C. MacIver, Forest Meteorologist, Atmospheric Environment Service (CCAI), Environment Canada, 4905 Dufferin Street, Downsview, Ontario, M3H 5T4; F. L. Raymond, 24 Royal Road, Aurora, Ontario, L4G 1A8; S. J. Masarovich, Forest Resources Group, Ontario Ministry of Natural Resources, 99 Wellesley Street, Toronto, Ont., M7A 1W3.

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Organizing and Applying Forest Climate Data

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Abstract

Individuals and small organizations often find it difficult to organize and use climate data they have collected. Recent advances in computer technology form the basis for procedures that can help one be more efficient in organizing and using the forest climate data that cost one so much trouble and time to collect. Frequently the available data cannot be used directly and must be incorporated into suitable statistical and physical models to produce a derived data set that can be applied to the problem at hand. The objective of the workshop is to have attendees discuss problems they have encountered and solutions they may have developed in using forest climate data. Attention will be focused on recent advances in data handling technology.

Résumé

Les chercheurs à titre privé et les petites organisations éprouvent souvent des difficultés à structurer et à utiliser les données climatiques qu'ils recueillent. Les derniers perfectionnements en technologie de l'informatique sont à la base de méthodes qui peuvent faciliter la structuration et l'utilisation des données sur le climat forestier, dont le relevé est si coûteux en temps et en efforts. Comme il est souvent impossible d'utiliser directement les données existantes, ces dernières doivent être incorporées dans des modèles statistiques et physiques appropriés afin de produire une série de valeurs dérivées qui peuvent servir à résoudre les problèmes étudiés. L'objectif de cet atelier de travail est de permettre aux participants de discuter des problèmes qu'ils ont rencontrés et des solutions qu'ils ont pu trouver en utilisant les données sur le climat forestier. On insistera surtout sur les progrès récemment accomplis dans le domaine de la technologie du traitement des données.

Introduction

Modern technology incorporated in data collection systems encourages individuals and small organizations to collect vast amounts of data. For example, three data loggers each with all 16 analogue and 4 pulse input channels fully utilized and outputting simple statistics such as hourly averages and daily maximums and minimums will accumulate the order of 3 megabytes of data over the growing season. Obviously it is easy to swamp oneself with data. One of the very powerful features of microprocessor based data collection systems is their ability to process data and only retain those statistics that are useful and necessary. It is well worth it to plan the data collection system carefully, ensuring no more data is being collected than is required. For example, it does not make much sense to collect average soil temperature every 5 min if daily average, maximum, minimum, and times of maximum and minimum will suffice. Presuming one has carefully planned the data collection system, however, it is still likely that large data sets will result. The natural tendency we all have is to collect supplementary statistics, which although they are not necessary for the immediate objectives may be useful for other needs.

Organizing the Data

Refer to Figure 1 for a schematic summary of Information Management Systems. The following list is presented to suggest a few concepts on managing data.

a) Data is organized according to what the data is to be used for and who is to use it.

b) Large complex data sets require that data be organized by some form of information management system. Software packages must suit the needs and level of sophistication of the user. Packages such as SAS and INGRES may be appropriate for the researcher in a super-mini or mainframe

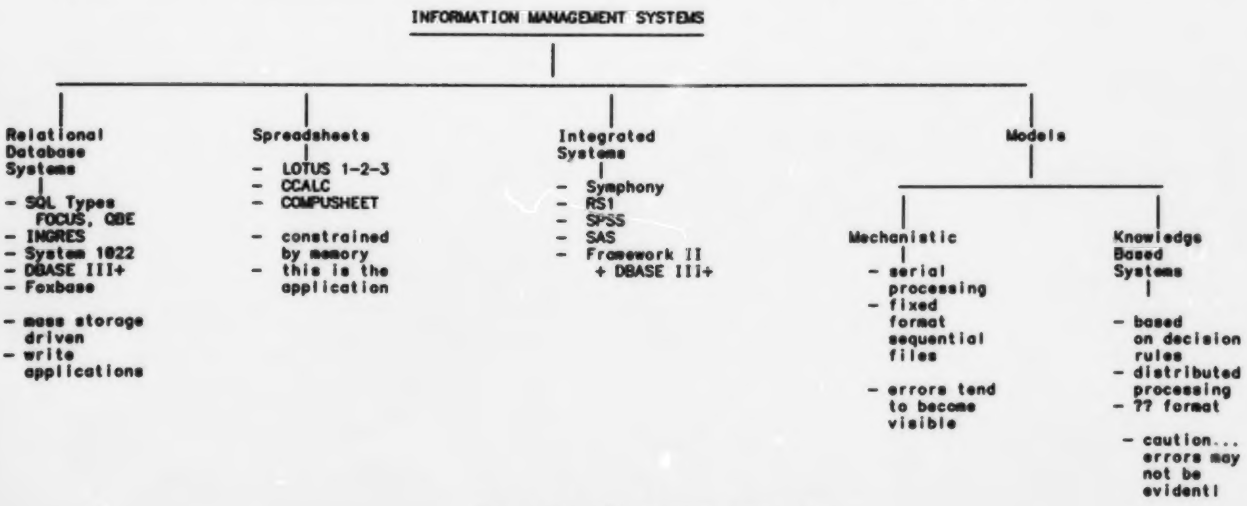
INFORMATION MANAGEMENT SYSTEMS
Relational Database Systems
- SQL Types FOCUS, QBE
- INGRES
- System 1022
- DBASE III+
- Foxbase
- mass storage driven
- write applications
Spreadsheets
- LOTUS 1-2-3
- CCALC
- COMPUSHEET
- constrained by memory
- this is the application
Integrated Systems
- Symphony
- RS1
- SPSS
- SAS
- Framework II + DBASE III+
Models
Mechanistic
- serial processing
- fixed format sequential files
- errors tend to become visible
Knowledge Based Systems
- based on decision rules
- distributed processing
- ?? format
- caution... errors may not be evident!

FIG. 1. Organizing forest climate data.

environment, but may not be suitable for use by a district forest office or company office. Packages such as LOTUS 1-2-3, DBASE III+, RS!, etc. (i.e., microcomputer packages) may be more familiar and appropriate.

c) As a minimum, the package must permit the user to access and manipulate data. Files must be capable of being read in a straightforward manner.

d) Where a reasonably large amount and diversity of data begins to accumulate, it is essential that documentation of the data sets be in place. Software packages that force documentation should be used. Fourth generation software packages tend to be self-documenting.

e) Software packages developed for mainframe environments are continually moving onto microcomputer systems. Consider adopting packages that can migrate easily between microcomputer and mainframe environments and between different operating systems.

Applying the Data

A list of some problems and possible solutions is presented in Table 1. Attendees are asked to suggest other problems and their success or failures in finding solutions.

TABLE 1. Problems and possible solutions.

Problem	Solution
Too many data	Consolidate Use Information Management System
Data needs correction or is unreliable	Correct or reject data
Not the right kind of data	Use physical and statistical models to derive data
Data not representative	
Too few data	Locate other data sets
Missing	Ignore or use preceding solutions

A Simple Example

Thermocouples were used to measure temperatures under the bark of a lodgepole pine tree during the winter of 1985-86. The example shows how a particular software product (SAS) was used to organize data and produce a summary.

Operational Software for Integrated Simulation of Weather and Soil Influences on Nursery Crops

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Abstract

A computer simulation model describing the unidimensional flow of water through a typically cropped nursery soil was developed. The model simulates the water balance of a dense, growing crop of seedlings that transpires in response to atmospheric demand for evapotranspiration and extracts water from a flow that percolates the soil matrix. The model is designed to function as a companion to the currently operational system of irrigation rate calculation that has been implemented at five provincial nurseries in Ontario. Weather input data for the model consist of hourly measurements of global shortwave radiation, air temperature, relative humidity, and wind.

The model has three main segments dealing with evapotranspirational demand, soil water flow and root uptake as well as several subroutines for data entry, calculation of local water-related soil characteristics, rain interception and crop development (sub- and supra-terranean). The evapotranspiration segment offers a choice of several widely recognized models, whereas the soil water flow is modeled according to Darcy's law of fluid circulation through porous media. This former segment has considerable versatility in handling a wide range of soils through a parameterized approach centered on local determinations of hydraulic conductivity and diffusivity with the recently released Guelph permeameter. The essential outputs of the model consist of potential evapotranspiration, actual consumptive use, and the water flow through the bottom of the root zone, that are calculated hourly and totaled for 24 h. It also has provision for drawing hourly on end-of-day soil water content profiles.

The model is both an instrument for understanding main physical processes subject to weather influences and an operational tool for optimizing irrigation and reducing nutrient leaching. Further developments will include rain risk analysis and a daily nitrogen balance segment describing uptake, leaching, and transformations.

Résumé

On a mis au point un modèle de simulation informatique qui décrit l'écoulement unidimensionnel de l'eau dans un sol cultivé de pépinière. Le modèle simule le bilan hydrique d'une plantation dense de semis en croissance, qui transpirent en réaction à la demande atmosphérique d'évapotranspiration et extraient l'eau d'un écoulement qui percole à travers la matrice du sol. Le modèle est conçu pour compléter le système opérationnel de calcul du taux d'irrigation qui a été mis en application dans cinq pépinières provinciales de l'Ontario. Les données météorologiques utilisées pour le système comprennent des mesures horaires du rayonnement global de courtes longueurs d'onde, de la température de l'air, de l'humidité relative et du vent.

Le modèle comporte trois segments principaux concernant la demande d'évapotranspiration, l'écoulement de l'eau dans le sol et l'alimentation radiculaire ainsi que plusieurs sous-programmes pour l'entrée des données, le calcul des caractéristiques locales du sol liées à l'eau, l'interception de la pluie et la croissance (souterraine et aérienne) des plantes. Le segment d'évapotranspiration offre un choix de plusieurs modèles largement reconnus, tandis que l'écoulement de l'eau dans le sol est modélisé d'après la loi de Darcy sur la circulation des fluides à travers un milieu poreux. D'une grande flexibilité, ce segment peut traiter une grande diversité de sols à l'aide d'une approche paramétrique axée sur des relevés locaux de la conductivité et de la diffusivité hydrauliques au moyen du perméamètre de Guelph mis en exploitation récemment. Le modèle fournit essentiellement des valeurs possibles d'évapotranspiration, de consommation réelle et d'écoulement de l'eau à travers le fond de la zone d'enracinement, qui sont calculées chaque heure et totalisées pour 24 heures. Le modèle peut aussi tracer des profils horaires de teneur en eau du sol en fin de journée.

Le modèle facilite la compréhension des principaux phénomènes physiques soumis aux effets météorologiques et constitue un outil opérationnel servant à optimiser l'irrigation et à réduire la perte d'éléments nutritifs par lessivage. Les perfectionnements à venir porteront sur l'analyse des risques de pluie ainsi qu'un segment sur le bilan quotidien d'azote décrivant les aspects de l'absorption, du lessivage et des transformations.

Introduction

Among various silviculture activities, seedling production in specialized tree nurseries is probably the most intensive and care-demanding technology. In the nursery stage, the growing conditions — ameliorated through irrigation, fertilization advection control, soil mixtures, and pest control — must preserve, undiminished, the potential of the superior trees from which the seeds were collected.

As pointed out by Huck and Hillel (1983), "a terrestrial plant lives in two realms, atmosphere and soil." The influences borne by crops from these media are complex and not fully understood. Although considerable progress in understanding these influences has been made through physiological research in agricultural crops, reaching as far into operational applications as applying artificial intelligence for growth factor optimization (Whisler et al. 1986), comparatively little is known about optimal procedures to grow tree seedlings. In Ontario, nursery growing technologies could be further improved by a careful reconsideration of weather and soil conditions. By choice, nurseries are located on sandy sites. This makes maintaining an adequate supply of water difficult because of the low water holding capacity of sandy soils. The result is that the seedling root zone is a very dynamic environment, often alternating between excess and complete exhaustion of accessible water. The inherently high drainage rate of sand results in a drying front which moves downward into the soil faster than the one caused by evaporation alone (van

Keulen and Hillel 1974). Under such circumstances, the top layer of soil, together with the seedlings, goes through diurnal cycles of stress and is notably prone to dessication.

Current nursery practices include sprinkler irrigation. The concentration of available water is increased in the top layer of soil with an amount sufficient to support the consumptive use during the next 2–3 d. However, an increased soil water content activates the downward movement of soil solute, and with this the leaching of highly soluble nitrogen fertilizers. Because solute movement in the unsaturated zone of soil is neither readily observed nor easily measured, the grower may perceive nitrogen disappearance from the root zone as uptake rather than leaching. However, administering fertilizers to permeable soils in subhumid areas may result in significant increases in leaching, even when irrigation is not practised (Meisinger 1976, Hill 1982). By increasing temporarily the soil moisture content, irrigation fosters a more active soil water transport. Careful nitrogen balances of sandy soils, prepared for intensively grown agricultural crops, both under rainfed and irrigated regimes (Watts and Hanks 1978), have shown that a sizable amount of fertilizer is leached into groundwater. Also, excessive or improperly timed irrigation may increase the amount of leachate. When results of fertilizer leaching studies are transposed in the microcosm of the nursery environment, it becomes evident that understanding of the soil solute movement plays a very important role regarding growth optimization, pollution avoidance, and improved effectiveness of water and fertilizers.

The use of computer models is particularly well-suited for gaining deeper insight into the integrated behavior of the atmosphere–crop–soil system. These computer techniques that incorporate large working memories and fast access to large environmental data sets are largely used in agricultural research, generally serving two main purposes: (1) incorporation of relevant physical and biological theory, and (2) behavioral examination of the simulated system subject to real-life environments.

Numerous models have been elaborated in the last two decades for almost every food/fiber crop. Many of these models have been based on the concept of water movement in a catenary process. This concept, first released by van den Honert in 1948, significantly developed by Gardner (1960), Cowan (1965), and most recently summarized by Whisler et al. (1986), remains the soundest approach to the phenomenon of stress development. However, when forest plants are considered, except for some recent attempts to model the atmosphere–forest–soil system, as applied to mature forests (Federer 1979, Jarvis 1981, Landsberg 1986), there have been few undertakings to apply the integrated approach to the study of water relations of tree species. Compared with the established forest, the nursery crop explores a very shallow soil layer, thus having access to only a limited soil water reservoir. Therefore a crop of seedlings, especially when recently undercut, may experience great stress when traversing a dry spell or even the peak diurnal demand for evapotranspiration.

The scope of this paper is to present partial results of a simulation model in which the essential determinants for the water relations of nursery crops are treated in considerable detail. The subsequent aim is to integrate the model with weather information currently available on an hourly basis at several nurseries in Ontario, as well as with recent progresses in testing soil hydraulic properties. These aims require compatability and dynamic interaction of three submodels concerned with: (1) atmospheric demand for evapotranspiration, (2) nursery crop water uptake, and (3) unidimensional water movement in soil, thus harmonizing information/knowledge from micrometeorology, tree physiology, and pedology. The model is seen as a process-oriented research tool, capable of yielding indications of the levels and rates involved in describing the soil water consumptive use and movement under naturally occurring conditions. The model can be used with the extensive weather data archives of the Atmospheric Environment Service, Environment Canada, for historical weather/hydrology explorations, as well as for comparisons between years or localities. When supplied with the information routinely collected at nurseries about weather, the model can be used in real time to give information about potential/actual evapotranspiration, soil moisture, suction head, available water and flux of water through the bottom of the root zone. The model can be made compartment specific through inclusion of locally measured hydraulic conductivity. By having the ability to accommodate a wide range of soil hydraulic properties, develop crops and continuously monitor weather conditions, the model has the capability to evolve into a crop simulator coupled with an expert system, similar to the one elaborated by McKinion and Lemon (1985).

Basic Concepts

The model reported in this paper simulates the net changes of soil water concentration along a typical nursery soil profile as a result of consumptive use, direct evaporation, and percolation outside the root zone. It allows for a specific depth definition of the root zone, which should correspond to the depth at which root undercutting is practiced. Water beyond this limit is no longer available for consumptive use and becomes flow to groundwater. The model can aid the study of exceptionally occurring phenomena upon the soil water condition: **natural** ones, such as heavy and prolonged rains or unusually high atmospheric demands for evapotranspiration, as well as **artificial** ones, such as abundant or deficit irrigation strategies.

The model should be conceived as an operational tool whose performance in the field would hold well for sizeable areas with uniform soil/crop characteristics. Apart from the weather elements, the main ground truth element of it is the hydraulic conductivity (locally measured or indirectly assessed). However, it would not be realistic to expect that the model's performance could be checked easily by point sampling outside the nursery environment, precisely because of the inherently high variability of the soil environment (Cameron 1979). For increased accuracy it is recommended to measure in situ the soil hydraulic conductivity with the recently released Guelph permeameter (Reynolds and Elrick 1986).

The atmospheric demand for **evapotranspiration** (ETp) is calculated hourly according to a method selected from among three possible equations: Penman, grass and alfalfa (Burman et al. 1983), and van Bavel (van Bavel 1966). For the interval to be simulated, actual data about air temperature and solar radiation, as well as air relative humidity and wind speed, are supplied, respectively, to the energy balance and the aerodynamic terms of the combination equation. Optionally, the model may be run with daily input data. In that case, the Priestley-Taylor equation (Priestley and Taylor 1972) is included among ETp equations.

The **canopy and rooting characteristics** are considered through the soil coverage and a root density distribution with depth in the soil profile (Moltz and Remson 1970, Feddes et al. 1976, Hayhoe 1981). Description of the variation of root density with depth represents the mathematical instrument through which the model "extracts" water from the soil at various depths. The assumption is made that the root system develops the same suction everywhere, but the actual root uptake from various layers depends on the layer's moisture concentration and root density (Feddes et al. 1974, Hayhoe and De Jong 1982).

The **physical properties** of the soil are considered by defining the water movement as a unidimensional flow of fluid through a homogeneous, rigid, and isotropic medium with a concomitant root extraction, as described by the continuity equation given by Childs (1969) and Moltz et al. (1968).

When moisture is not limiting, the **actual evapotranspiration** of the crop of seedlings is assumed to proceed at the potential rate, with a partitioning between crop transpiration and bare soil evaporation controlled by soil coverage, as in the procedure applied by Nimah and Hanks (1973). As the soil dries, both the direct soil evaporation and the root extraction are reduced, the former depends on the rate of upward water movement whereas the latter depends on a difference between actual soil suction head and maximum root suction. At limit, the boundary condition is set to wilting point.

Main Computational Steps

The simulation starts by accepting information about locality, latitude, and elevation, and continues with a specification for thickness of root zone, taken by default to 30 cm, and layers of a grid necessary for root density generation and discretization of the space variable (Remson et al. 1971). The time step, input file type (hourly/daily), and hardcopy output are specified next.

Subsequently, the values for field-saturated hydraulic conductivity, wilting point, and soil moisture at saturation are input. Thus, if specific measurements were made for various nursery compartments, the model can be run with soil parameters measured in situ. Otherwise, at this point, a screen menu will display default options for a qualitative specification of soil texture class, with the following categories: sand, loamy sand, sandy loam, loam, sandy-clay-loam, silty-clay-loam, clay loam, sandy clay, silty clay, and clay. For the specified class, the model chooses the standardized soil suction head, volumetric water content, and hydraulic conductivity for water-saturated condition, as given by Clapp and Hornberger (1978). Then, by default, the suction head is set for field capacity and wilting point at 300 and 15 000 cm (1.5 MPa), respectively. The initial soil moisture is then specified. If not known, or when simulations are run for a whole growing season, the initial soil moisture content may be set to moisture at field capacity for a certain texture class. This is based on the assumption that such would have been the soil moisture condition after thaw or following a significant rain event during spring.

The time interval for the run is then input as first day and last day of the simulation. Then the model opens the weather input file (hourly or daily) and two output files (hourly values and daily summaries) for calculation of soil water parameters, actual transpiration, surface evaporation, and flow through bottom of root zone. Subsequently, these files become inputs to graphics packages.

The input file contains data necessary to calculate ETp according to chosen formulae, and to add current precipitation to soil profile: air temperature (dry bulb, wet bulb, and dew point), wind run, air relative humidity, cloudiness (amount and opacity), global shortwave radiation, and net radiation. If the hourly file option is selected then a whole day (24 records) is input and stored. Otherwise, only one record with daily averages/sums of same weather elements is input. The evapotranspiration subroutine is now called. In the case of hourly files, the ETp equation, for which a choice was made, is solved for every hour. Alternatively, the equation is solved with data for the whole day, so as to yield directly the daily ETp. Then this value is spread by hours of daytime by means of a sine function, using the daily calculated daylength.

At the inner, hourly, loop the model constructs virtually a grid over the soil profile for solving the continuity equation. The network of nodes is described through a space ordinate, which is the profile depth, and a time abscissa, with the interval set to nine time steps (Remson et al. 1971, Feddes et al. 1976). When the continuity equation is described for all nodes of network (layers x time steps), it results in a system of simultaneous linear algebraic equations that is solved in a separate subroutine using tridiagonal Gaussian elimination for specified boundary conditions. The outputs consist of new values of unsaturated hydraulic conductivity, soil water diffusivity, suction head and soil moisture concentration at the nodes. The crop's actual transpiration, actual soil surface evaporation, and the flow of water through the bottom are calculated at the end of the hourly loop and their daily summaries are updated. When all the hourly loops are completed, a record is written in the daily output file and a hardcopy form with daily summaries is printed, if desired.

The code of program is about 35K. It is written in BASIC language and can be run on an MS-DOS computer with IBM Basic Compiler 2.0 or Microsoft QuickBasic.

Simulation Trials

A series of simulation runs were performed to assess the influence of texture (implying influence of hydraulic conductivity), rain distribution, and degree of crop cover during 1 mo on output parameters such as moisture content, suction head, and flow through bottom of root zone.

Simulations were performed with two soils at the OTIFBI nursery, Maple, Ontario. In both places the saturated hydraulic conductivity was determined in situ with the Guelph permeameter, resulting in Ksat = values of 0.1970 (Soil 1) and 0.0427 cm/min (Soil 2). The unsaturated hydraulic conductivity function was calculated by the method used by Hayhoe and De Jong (1982). The soil profile considered for these runs was 30 cm deep, arbitrarily divided into seven layers of increasing thickness. Crop parameters were chosen to represent a typical conifer nursery crop, such as transplants in the 2nd yr. The root distribu-

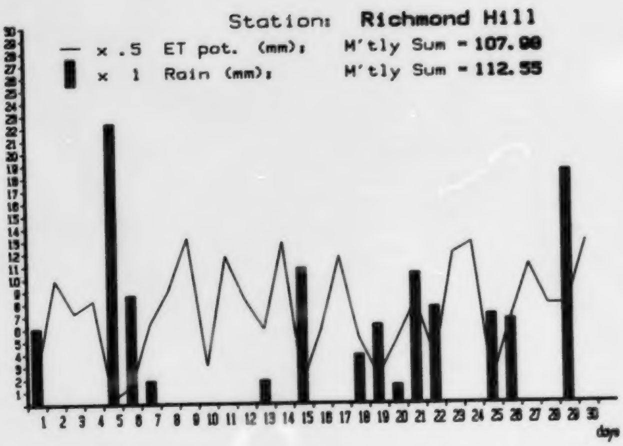

FIG. 1. Potential evapotranspiration and precipitation, June 1982.

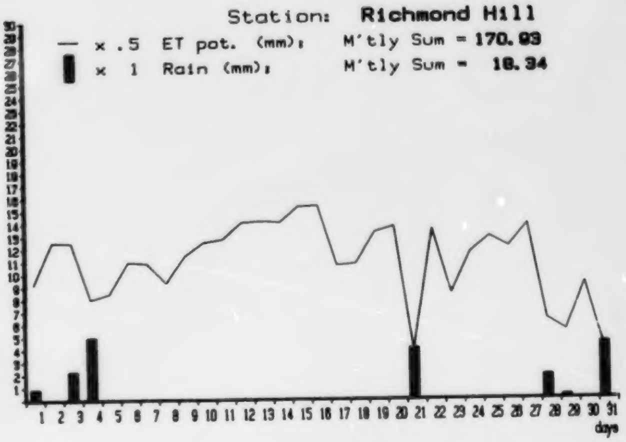

FIG. 2. Potential evapotranspiration and precipitation, July 1983.

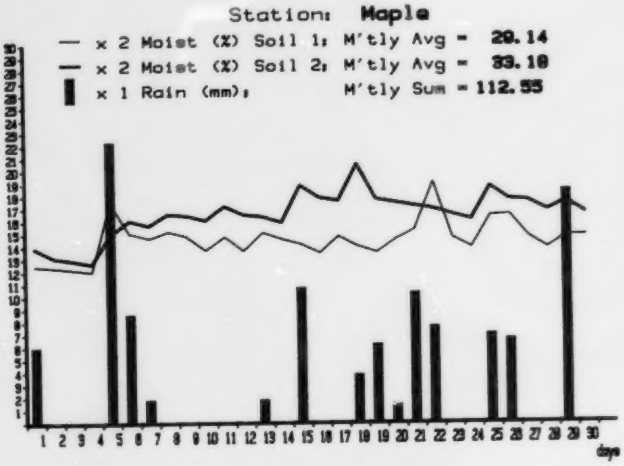

FIG. 3. Precipitation and soil moisture content at 15-cm depth, June 1982.

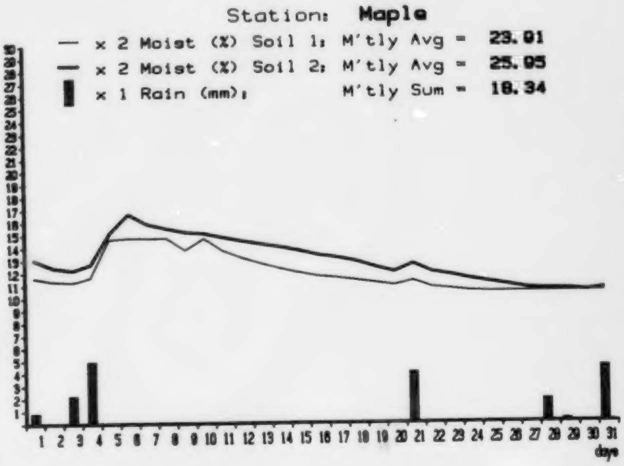

FIG. 4. Precipitation and soil moisture content at 15-cm depth, July 1983.

TABLE 1. Rains and potential evapotranspiration (Penman, grass) for June 1982 and July 1983 (mm).

Period	Rain		Potential evapotranspiration
	Events	Amount	
June 1982	14	112.55	107.98
July 1983	7	18.34	170.93

tion was simulated with the distribution given in Feddes et al. (1976). However, the root amount was forced to zero at the depth of 30 cm, thus simulating a clear-cut bottom to the root zone, such as expected following a nursery root undercutting operation.

The model was tested with meteorological information from two very different summer months: **June 1982**, a cooler than normal month, with numerous rains at short intervals, and **July 1983**, a warmer than normal month, with few and small rains.

The water supply and the atmospheric demand for evapotranspiration regime for the 2 mo present significant differences (Figs 1 and 2). Whereas in June 1982 potential evapotranspiration is obviously depressed, mostly by reduced insolation and atmospheric saturation deficit, the July 1983 is characterized by long intervals of high ETp, due to high air temperature and cloudless skies. Quantitatively, the water input and potentially evapotranspired during the 2 mo, presented in Table 1, shows that the rain amount was higher than ETp during June 1982. Although the magnitude of the 14 rain events had a range of 22.3 mm/d, the consumptive use on these days was very low (Fig. 1). Such amounts of water could not possibly be stored in a 0.3 m depth of soil, particularly when the rain events occurred in sequence, such as the intervals 5–7 June (32.7 mm) and 18–22 June (29.3 mm). Consequently, in those intervals, the percolation processes were very active. The situation was completely different in July 1983 when, even if soil was fully saturated at the beginning of month, a cumulated ETp of 170.7 mm could not be sustained from seven rain events totaling only 18.3 mm, without a significant depletion of moisture and increase of suction head.

The influence of hydraulic conductivity on the soil water movement appeared to be a major factor regarding steadiness of water supply, as well as to fluctuations of soil

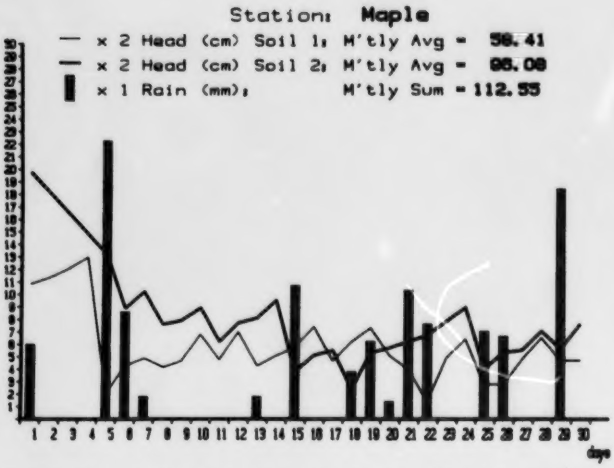

FIG. 5. Precipitation and soil suction head at 15-cm depth, June 1982.

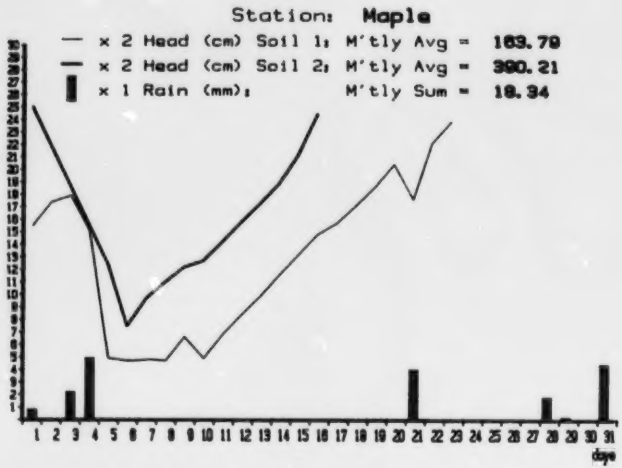

FIG. 6. Precipitation and soil suction head at 15-cm depth, July 1983.

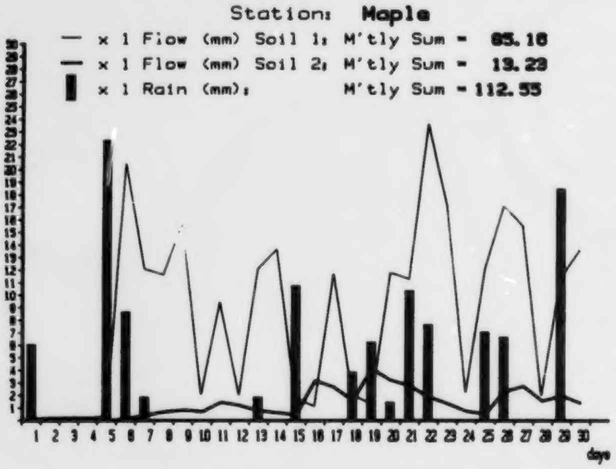

FIG. 7. Precipitation and flow-through bottom of root zone, June 1982.

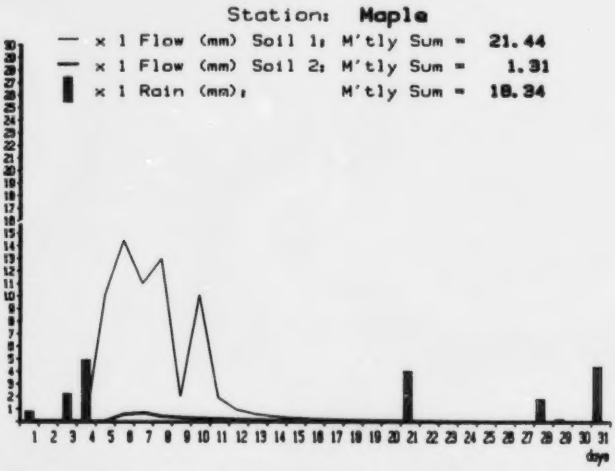

FIG. 8. Precipitation and flow-through bottom of root zone, July 1983.

suction head caused by rains and their subsequent exhaustion. Soil 1, coarser and with a higher soil water conductivity, displayed greater variation of soil moisture, soil suction head, and flow through bottom of root zone than Soil 2, which was a finer texture. The evolution of soil moisture at 15 cm depth, presented in Figs 3 and 4, clearly shows the influence of rains and consumptive use, and the model's sensitivity. In general, Soil 1 was holding water for a considerably shorter amount of time than Soil 2. In the more permeable Soil 1, water percolated in many cases before it had a chance to be extracted by roots or directly evaporated from the bare soil surface. It is also noteworthy that during a rain event and shortly after, the ETp is low because of reduced energy input (cloudiness) and small saturation deficits. In all cases the greatest soil water deficit is experienced by the topmost soil layer.

From the ecological viewpoint, the most important index for soil environment characterization is the suction head. In the model, the maximum root extraction head is set to 15 000 cm, although it is known that several species can develop plant suction heads considerably higher than this value (Kramer 1983). If the soil suction head reaches this threshold, the roots would not be able to extract water. When viewed from this perspective, the water supply conditions of June 1982, with numerous rains at short interval, can be considered prone to percolation but not stressing. Consequently, the soil suction head was low and water was readily available (Fig. 5), while the flow of water through the bottom of root zone was considerable (Fig. 7). The few and light rains of July 1983 were conducive to a continuous depletion of soil moisture, as well as high values for the soil suction head (Fig. 6). In the same interval, the flow through the bottom (Fig. 8) appeared only for a short interval after the rain events and was much diminished compared with June 1983.

When the two soils are compared, it is noticeable that (1) under abundant watering regime the percolation is almost immediate for the coarser soil, while it is reduced and delayed for the finer soil, and (2) when precipitation events are scarce the finer soil offers more water to the crop because its percolation is very small.

For Soil 1, which is closer to normal nursery conditions,

TABLE 2. Simulated soil evaporation and root water extraction by degree of soil cover (mm).

Cover degree	Soil evaporation	Root extraction	Actual ET	% ETa/ ETp	% REX/ ETp
	June 1982 — cloudy and rainy month				
.5	54.81	22.29	77.10	71.46	20.66
.8	21.93	33.99	55.92	51.83	31.50
	July 1983 — sunny and dry month				
.5	86.08	73.42	159.50	93.43	43.01
.8	34.41	117.98	152.39	89.27	69.11

the influence of the degree of cover on actual soil evaporation and root water extraction is given in Table 2. In both months, a higher coverage results in increased root extraction (REX). Conversely, when the coverage is reduced the direct soil evaporation takes high values. When the simulated actual evapotranspiration (ETa) of the 2 mo is compared, obviously for June 1982 its value was smaller than for July 1983 not because of the lack of water but as a result of reduced atmospheric demand, due mostly to cloudiness of that month. The situation was reversed in July 1983 when the ETa came closer to ETp, although rainfall was scarce. The proportion of root extraction to ETp also reflects the influence of the degree of coverage on consumptive use of water.

Outlook

Modeling of soil water movement within the nursery crop environment allows us a glimpse at the dynamics of water availability in the root zone. It shows, with poignancy, that the same rain or irrigation event leads to a different allocation of water between the main elements of the water balance: actual evaporation, root extraction and percolation, depending on the local hydraulic conductivity and actual evapotranspiration.

In the subhumid environment of Ontario, typical for its low advection, the strategy of the supplementary irrigation should be guided by the crop's status or age. Well-established crops should be irrigated according to a **deficit** strategy, in which water is more uniformly available. The objective should be the minimization of percolation and, with this, of fertilizer leaching. It is appreciated that requirements of this strategy would be well suited if Ontario's currently grown conifers seedlings were supplied with irrigation rates equal to the Penman grass standard of potential evapotranspiration. However, the hardwood seedlings should be irrigated, at a maximum rate, with the Penman alfalfa standard. These recommendations are, of course, made in absence of more detailed studies, although under the climatic environment particular to Ontario's nurseries such studies are not likely to yield significant differences from one crop to another. This is because the parameters of the energy and mass balance are not likely to be too far apart. Because the greatest moisture concentration and suction head variations occur in the most superficial layer of the soil, the shallowly rooted or very young crops may have to be irrigated according to an **abundance** strategy. This may sometimes mean irrigating several times a day, although this could create additional percolation problems. Likewise, this same strategy should be applied immediately following the transplanting operation, before the seedlings started new roots.

Due to the rapid infiltration of water in sandy soils, a clear recommendation results from the model regarding the timing of watering. Irrigation should normally be administered during mid- to late morning, so that water is available before the hours of peak demand, which most commonly occurs between 11 AM and 2 PM. If watering is applied late in the afternoon or evening the majority of it would percolate before the peak demand of next day.

Given the importance of soil hydraulic conductivity for the growing environment and knowing that it has considerable field variation, it is necessary to have the nurseries mapped for this property and, most importantly, the crops allocated to compartments depending on their assumed resistance to the soil water stress that potentially could develop in a certain place if the irrigation is not applied at the proper time. In practice, this means that the sowings for transplants should avoid coarse soils. However, the soil water properties can be temporarily changed through addition of swelling matter, such as peat moss, that reduce percolation while giving the roots unrestrained access to water.

The usefulness of this model lies mostly in assessing potential effects of various irrigation strategies on hydrologic and physiologically significant parameters. Also, the model may help estimate the leaching amount in the case of essential fertilizers, such as nitrogen, which are administered as very soluble substances, like nitrates. The model may have an expanded use, to a community of trees, if the soil layer description and the root water extraction modules are appropriately modified. In that case, the model may help explain those environmental influences on growth that are related to soil water stress. Further development of this area of ecological research may find very direct operational applications through an expert system. The same would include in its knowledge base data about local soil and crop, while its inference engine would aim to devise an irrigation schedule that would consider both the rain probability for a certain cluster of "dry" days and minimization of the flow-through bottom.

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Airborne Thermography as a Tool in the Design of Ditch Networks for Forest Drainage Programs

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Abstract

False-color infrared aerial photography can provide the forester with information on surface moisture conditions as they exist before ditching. The technique is particularly useful in open areas or areas of thin forest cover, but the macro- and microdrainage channels can be mapped even in areas of denser forest cover. Natural macro- and microdrainage networks can be detected on aerial thermography as well. Thermography also permits the identification of surface and near surface moisture accumulations, either moving or stagnant. By establishing the degree and direction of water movement at or beneath the soil surface, foresters can make decisions concerning ditch placement and gradient, and network density. Table 1 summarizes the interpretation keys used in this project to extract information on soil moisture from remote sensing imagery. After the ditching has been completed, aerial thermography provides a useful means of monitoring the degree of effectiveness of the ditch network in removing excess moisture from the site. Follow-up information allows the planner to "fine-tune" the drainage network for optimum performance.

Résumé

La photographie aérienne à l'infrarouge avec fausses couleurs peut fournir au forestier de l'information sur les conditions d'humidité en surface avant le drainage. Cette technique est particulièrement utile dans les secteurs à découvert, ou lorsque le couvert forestier est clairsemé, mais les macrochenaux ou microchenaux de drainage peuvent être cartographiés même dans les forêts denses. Les réseaux de macrochenaux et de microchenaux naturels de drainage peuvent être repérés aussi par la thermographie aérienne. La thermographie permet également l'identification des zones d'humidité à la surface et près de celle-ci, que les eaux soient en mouvement ou stagnantes. En établissant le degré et la direction du mouvement de l'eau à la surface du sol ou au-dessous, les forestiers peuvent choisir l'emplacement et l'inclinaison des fossés ainsi que la densité du réseau. Le tableau 1 résume les clés d'interprétation utilisées dans ce projet visant à extraire de l'imagerie de télédétection une information sur l'humidité du sol. Après l'achèvement des fossés, la thermographie aérienne peut constituer un moyen utile de surveiller leur capacité d'éliminer l'humidité excessive du terrain. Des données de suivi permettent au planificateur «d'améliorer» le réseau de drainage pour un rendement optimal.

Introduction

The technique of draining wetlands to improve forest growth has been practiced in Europe for more than 100 yr. Draining the moisture from organic soils has been shown to improve oxygen supply to the rooting layer. In addition, a decrease in soil moisture permits heat to penetrate the soil more readily, particularly in early spring, thus effectively lengthening the growing season (Ecological Services for Planning 1985).

To design an effective drainage network requires intensive ground survey of the slope, and the depth and quality of the peat. Besides furnishing a base map of the study area, remote sensing imagery can provide information needed for determining slope, microdrainage, soil moisture, and the location and extent of some forest types. At the planning stage, remote sensing coverage permits large areas to be pre-stratified according to accessibility and biological differences. Less intensive ground survey is needed as a result. In an operational program to drain organic soils, the use of remote sensing to supplement ground surveys would save both time and money, as much of the assessment could be carried out in an office setting.

To test the effects of draining organic soils in the Clay Belt of Northern Ontario, the Northern Forest Development Group of the Ontario Ministry of Natural Resources began conducting an operational drainage project of a 400-ha site 25 km east of Cochrane. In accordance with practices in Europe, large-scale (1:10 000-scale) topographic maps prepared from large-format panchromatic photography were used in planning the ditch network. Intensive ground surveys were carried out by consultants and sites were classified to forest ecosystem classes (see Jones et al. 1983). To provide a broader perspective on the study area, the Ontario Centre for Remote Sensing recorded medium-scale aerial photography and thermography of the test site and surrounding area. This imagery was to be used in identifying microdrainage channels across a large cutover.

Methodology

Large-format (23 cm × 23 cm) color infrared photography at a scale of 1:16 000 was obtained over the site in May of both 1985 and 1986. As part of the same operation, aerial thermography was recorded in two channels at a scale of 1:30 000. A swath of coverage nearly 4000 m wide was produced, providing imagery of about 4000 ha around the 400-ha test site. The test site itself included the cutover which was to be ditched as well as an area of mature black spruce forest where ditching had been done in the winter of 1984/85. The remainder of the test site provided a control area where the same organic soil conditions existed but where no ditching was planned. The 1985 aerial coverage was used together with the ditching plan which was to be carried out in the cutover during the summer of 1985. The imagery was also used to monitor the effect of an earlier drainage program carried out in the mature forest. The 1986 coverage was recorded to monitor the effect of the new ditching on the cutover.

Photography

As stated above, color infrared film (Kodak, Aerochrome Infrared 2443) was used to obtain the test site photography.

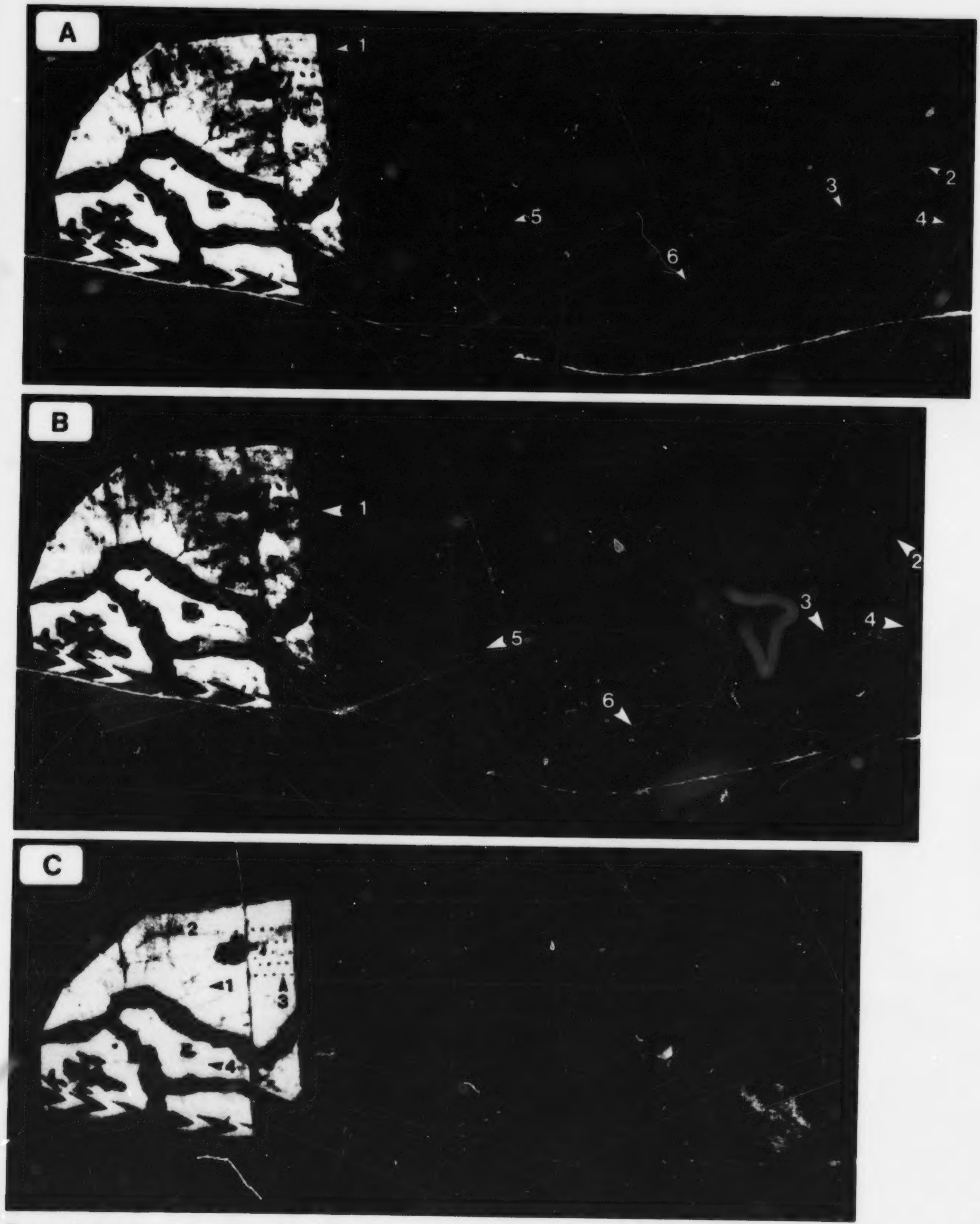
A
1
2
3
5
4
6
B
1
2
3
4
5
6
C
2
1
3
4

FIG. 1. A) Analogue thermography, May 1985; B) level-sliced thermography, May 1985; C) level-sliced thermography, May 1986.

The film is sensitive in the 500-900-nm region of the spectrum (when used with a 500-nm long-pass filter). This range includes the red and green wavelengths (500 - 600 nm and 600 - 700 nm, respectively), but also the near-infrared wavelengths (700 - 900 nm), which are recorded in the red dye of the infrared emulsion layer. Color infrared film is generally used for studies concerned with vegetation health. The abundant chlorophyll in most healthy plants reflects nearly 35% more radiation in the near-infrared range than in the green range, so differences in health from one plant to another are evident from differences in infrared reflectance levels. Color infrared film also serves to enhance differences in surface moisture. Water absorbs infrared energy, so moist areas are recorded as dark patches in the red emulsion layer of the film.

Thermography

A Daedalus Dual-Channel Thermal Infrared Line Scanner was used to detect emitted energy from the test site in two channels: 4.5–5.0 μm and 8.5–14.0 μm. The peak spectral emission of earth temperatures normally occurs near 9.5 μm, so the single channel of recording (8.5–14.0 μm) would normally be adequate for recording the energy emitted from the soil surface. As the temperature of the soil on the test cutover was expected to be rather high, however, the second shorter wavelength channel was recorded as well. Recording data in both spectral bands provided for the detection of the warmer surface temperatures of the cutover and also the cooler surface temperatures of the mature forest.

The detection of surface and near-surface water using aerial thermography is based on the principles of thermal inertia for wet and dry sandy soils (King 1982). According to these principles, moist soils tend to warm more slowly than dry soils, but also tend to retain stored heat longer.

On the basis of King's results, the aerial thermography was recorded at 1000 h local time. It was expected that by this time of day the temperature of the surface soil on the open cutover would have risen quite rapidly from solar heating. The effect of heating was expected to be more extreme in relatively dry organic soils with low thermal diffusivity values than in organic soils with a high moisture content and correspondingly higher diffusivity values (Oke 1978). The difference in moisture content was thus expected to have thermal expression on the imagery.

In the mature forest, on the other hand, the accumulation of surface and near-surface water would have absorbed short-wave radiation during the day and emitted energy in long-wave radiation, more slowly, at night. The result would be a net energy flux convergence in the soil beneath the forest canopy. A contrast would thus result on the midmorning imagery between the stored heat of the saturated soils and the cooler, drier soils.

Interpretation of Drainage Across the Cutover Before Ditching

Figure 1A is an analogue print of the short-wave thermal infrared data (covering the 4.5 to 5.0-μm range) recorded in May 1985, before the ditch network had been dug on the cutover. The apparent surface temperatures represented on this image range from 6°C (represented by pure black) to 25°C (represented by pure white).

The cutover, identified as "1" on Figure 1A, appears relatively warm (white) on the whole, but several cold (black) anomalies are also in evidence. One of these features occurs along the creek shoreline. Another consists of a row of chevron shapes that indicates a line of trees, mostly black spruce, that had been left standing along the road (as a wind break and for aesthetic reasons).

Linear, relatively cool anomalies that occur across the cutover have been interpreted as microdrainage features. Color infrared photography of the cutover supports this interpretation by showing the linear features to be dark (i.e., infrared-absorbing), moist depressions. Apart from these features, most of the surface appeared on the photography to be dry. Ground surveys conducted at the time the imagery was taken, however, reported a higher moisture content. The presence of relatively cool soil patches on the analogue thermography was more in keeping with that finding.

When the thermography was re-sampled within a narrower temperature range, the cool features became even more apparent, as illustrated by the enhanced level-slice in Figure 1B. On this image, the linear features in the cutover (site no. 1) extend into the area around the north fork of the creek. The dark patches to the north and east of the creek tributaries are enhanced, indicating generally cool soils in these areas. The southeast lobe of the cutover between the creek tributaries is now visibly cooler than the surrounding terrain of the cutover. The appearance of thermal contrasts across the cutover before ditching, the fact that the creek provided drainage for the site, and the dry appearance of the cutover terrain on the infrared photography, all combine to indicate that the cool, dark patches on the thermography represent areas of **subsurface** moisture accumulation. The continuation of the linear features to the creek thus indicated the flow of subsurface water.

Interpretation of Moisture and Drainage in the Control Area

The thermography of the mature forest outside the cutover revealed some areas of relative warmth. These areas correspond to sites of high moisture content and poor drainage. Stagnant water at these sites absorbed heat over a longer period than better-drained areas could. A net heat flux convergence occurs in areas of stagnant water, whether the tree canopy is dense or open.

Examples of heat storage were found in the control area at site "2" on Figures 1A and B. Ground surveys in the control area showed that the warm patches of forest correspond closely to the forest type identified as Operational Group Type 14 (Jones et al. 1983). OG 14 identifies black spruce treed bog with wet to very wet soil moisture conditions and very poor drainage. The forested site marked as "3" on Figures 1A and B was also identified as type OG 14. Ditches had already been dug at that site, with a spacing of 30 m. Both sites no. 2 and no. 3 would appear to have a high moisture content and a considerable amount of stagnant water, despite the existence of a ditch network at site no. 3. The high level of brightness (warmth) at site no. 3 and the large size of the bright area indicate the severity of water accumulation or ponding: perhaps drainage has simply been unsuccessful at this site. In addition, water may be flowing into this site from an upslope area to the east (site no. 4). The flooding of site no. 3 may thus be stimulated by the very ditching intended to drain it.

The cooler temperatures of site no. 5, a previously ditched site that also supports forest type OG 14, indicate the successful drainage of moisture into the collection ditch and settling pond. At site no. 6, in contrast, the area around the collection ditch is flooded. The movement of moisture through the soil may be constricted at this point and the flooding may have resulted from the backup of this water.

Interpretation of Drainage in the Cutover After Ditching

Drainage ditches were dug in parts of the test cutover in the summer of 1985 at approximately 20-m intervals. Figure 1C, a 1:30 000-scale analogue thermograph of the study area, shows the location of the drainage lines at sites nos. 1, 2, and 3.

Comparing the 1985 and 1986 thermography reveals changes in the moisture regime across the cutover as a result of the ditching. The most dramatic change appeared at site no. 1 on Figure 1C, where soil surface temperatures were warmer than temperatures at the same site in the spring of 1985 (Figs 1A and B). The drainage network constructed here had been effective in removing soil moisture. The fact that the area to the north of the drainage complex, at site no. 2 (Fig. 1C), was still cool indicated an accumulation of subsurface water in this area. Site no. 3 (Fig. 1C), the north sector of which had appeared moist (cool) on the 1985 thermography, now seemed to have been effectively drained as well.

The interfluvial portion of the cutover at site no. 4 (Fig. 1C) had been intensively ditched, and appeared to be just as dry as it had been the previous year. The intensive drainage network had apparently caused no change in the effectiveness of drainage at this site.

TABLE 1. Keys to identification of surface and subsurface moisture features on aerial thermography for forest ditching project in Northern Ontario.

	In open forest	In mature forest
Surface moisture: stagnant or accumulated	Spread-out patches (as opposed to linear features), cooler than adjacent cutover	Spread-out patches (as opposed to linear features), warmer than surrounding forest
Subsurface moisture:	Patchy-to-linear cooler thermal anomalies	Not visible
Surface and subsurface moisture flow:	Linear, relatively cool thermal anomalies	Linear, relatively warm features

Conclusion

When used in an operational program of wetland drainage, remote sensing can reduce the requirement for ground surveys. Detailed mapping of candidate areas can be accomplished more quickly from the remote sensing imagery than from the analysis of data from traditional ground surveys. Although the need for ground truth can never be eliminated, the productivity of time spent performing the sampling can be increased. The result is that by using simple interpretation techniques, remote sensing can save time and money.

Acknowledgment

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Model for Operational Spraying Events Under Different Weather Scenarios

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Abstract

The aerial application of pesticides is becoming a major dispersal mechanism for both insecticides and herbicides. Extensive field studies have quantified the effects of operational and meteorological parameters on ultimate deposit and drift. Models are now being used to evaluate off-target deposit for worst-case spray scenarios. The predictions of one such model, FSCBG, are investigated for a herbicide spray with the results being used to calculate a buffer zone to ensure a "tolerable" off-target deposit.

Résumé

La pulvérisation aérienne devient un mécanisme majeur de dispersion des insecticides et des herbicides. D'importantes études réalisées sur le terrain ont permis de quantifier les effets des paramètres opérationnels et météorologiques sur la dérive et le dépôt définitif. On utilise maintenant des modèles conçus pour évaluer les dépôts hors-cible dans les scénarios de pulvérisation de pire éventualité. On examine les prévisions d'un tel modèle, le FSCBG, pour une pulvérisation d'herbicide, les résultats servant à déterminer une zone tampon qui assure un dépôt hors-cible «tolérable».

While recognizing that society, as a whole, is the beneficiary of yield increases due to the reduction of pest damage, public concern continues about the effects of pesticide spray in agriculture and forestry. Average annual forest losses from insects and diseases over the 5 yr from 1977 to 1981 has been estimated at 107.4 million m^3 or roughly 73% of the 1982 harvest of 147 million m^3 (Statistics Canada 1986). During this period, nearly 41% of the loss was attributed to mortality or growth reduction from spruce budworm infestations. In a well-established aircraft spray program during this period, over 4 million ha of forest were treated annually, with the majority of spraying taking place in New Brunswick and Quebec. However, Ontario has recently incurred a substantial budworm outbreak.

The off-target transport and dispersion with subsequent environmental impact of chemical spraying is a continuing concern. The DESIRE is to target the entire spray to these areas of concern. The REALITY is that a fraction and often a sizeable fraction of the spray drifts to off-target locations. The GOAL, therefore, is to minimize the environmental insult to these nontarget areas to a tolerable level through the regulation of buffer zones. However, buffers should not be unnecessarily large because this could impede efficient forest management. Meteorological factors can play an important role in the ultimate fate of the spray material. The ROLE of models is to provide a tool to operators whereby informed decisions can be made on appropriate conditions to optimize target coverage. Provincial regulators, on the other hand, can utilize these same models to predict off-target deposit for worst-case scenarios and thereby set buffer zones to ensure environmental protection.

The existing pesticide drift and deposition models can essentially be categorized into two basic types, diffusion and ballistic models. The former is particularly suitable to Ultra low volume (ULV) sprays where the principle mechanism for spray drift and deposition is the diffusion resulting from atmospheric turbulence. The ballistic models are more appropriate to herbicide (large droplet) applications where the spray droplets move downward simply by gravity. In a model evaluation (SENSE 1984), 11 available models were identified that could be used for aerial drift assessment. Of these models, three in particular were identified which could be used for aerial drift assessment. Of these models, three in particular were identified as being superior:

1. the FSCBG model (*F*orestry *S*ervice, *C*ramer, *B*arry, *G*rim, Dumbauld et al. 1980) useful for large droplets sprays in forestry applications.
2. PKBW (*P*icot, *K*ristmanson, *B*aska-Brown, *W*allace, Picot et al. 1986) useful for ULV spraying in forestry applications.
3. and AGDISP (*AG*ricultural *DISP*ersion Model, Teske 1986, Bilanin and Teske 1984) useful in an agricultural context for large droplet spraying.

All three models have, to varying extents, incorporated the necessary components to model the various aspects of the overall release, dispersion, and deposition processes (Fig. 1). Within the spray release zone, the droplet spectrum is controlled primarily by nozzle design, formulation base, aircraft speed, nozzle location on the aircraft, and injection angle of the spray jet to the airstream. Aircraft-induced vortices act as an efficient pesticide carrier to move the spray cloud closer to the target before influence by background turbulence. When vortex breakdown occurs, large quantities of pesticide can be dispersed at the effective release height contributing significantly to off-target drift. Once the droplets are airborne, they undergo evaporation, thereby reducing their size and making them more susceptible to turbulent dispersion and ultimate drift. Once deposited within the canopy, droplets will impact on foliage or continue to settle through the canopy until impacting the ground. Changes in the windspeed profile and turbulent structure within the canopy strongly influence the droplet trajectory and turbulent dispersion.

An example of the modeling capability of the FSCBG Model is presented for a conifer relief spray (Fig. 2) using the glyphosate herbicide "Roundup". The model scenario is for an AG-5 Bell helicopter spraying from a height of 25 m above a relatively smooth clearcut area. A volume mean diameter for the spray spectrum of 435 μm was attained through the use of D6-46 nozzles oriented backwards with a boom pressure of 275 kPa. The herbicide Roundup® was assumed to be applied at a rate of 5.6 L/ha in an aqueous solution at a total rate of 45 L/ha. A 100-ha area was sprayed using a swath width of 25 m. Stability was assumed to be neutral with an average air temperature of 21°C

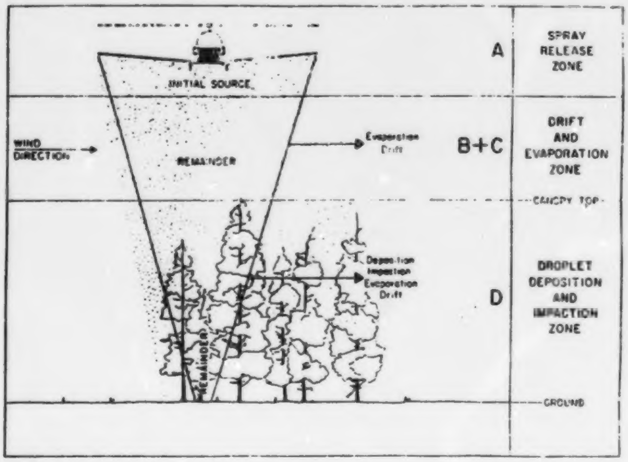
INITIAL SOURCE
A
SPRAY RELEASE ZONE
WIND DIRECTION
REMAINDER
Evaporation Drift
B+C
DRIFT AND EVAPORATION ZONE
CANOPY TOP
Deposition Impaction Evaporation Drift
D
DROPLET DEPOSITION AND IMPACTION ZONE
REMAINDER
GROUND

FIG. 1. Physical processes involved in pesticide spray release (Grim and Barry 1975).

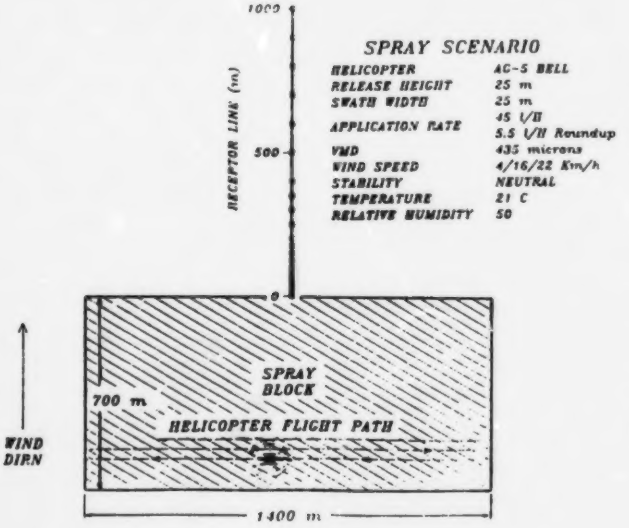
1000
500
0
RECEPTOR LINE (m)
SPRAY SCENARIO
HELICOPTER AG-5 BELL
RELEASE HEIGHT 25 m
SWATH WIDTH 25 m
APPLICATION RATE 45 l/H
5.5 l/H Roundup
VMD 435 microns
WIND SPEED 4/16/22 Km/h
STABILITY NEUTRAL
TEMPERATURE 21 C
RELATIVE HUMIDITY 50
SPRAY BLOCK
700 m
HELICOPTER FLIGHT PATH
WIND DIRN
1400 m

FIG. 2. Conifer relief spray scenarios.

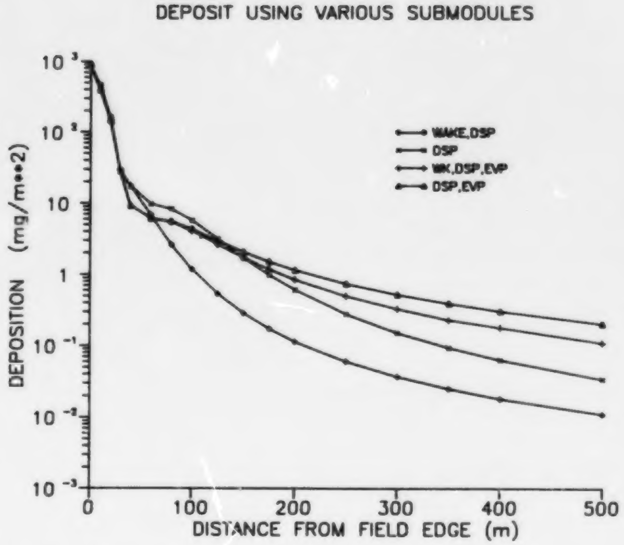

FIG. 3. FSCBG model results using various submodels for 4 km/h wind speed.

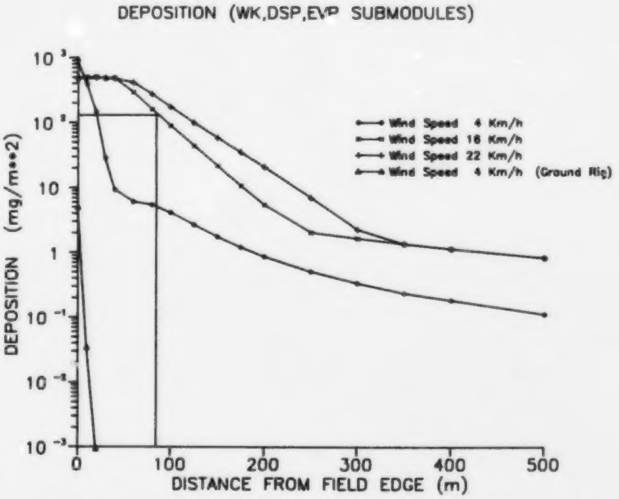

FIG. 4. FSCBG model results for various wind speeds.

and a low relative humidity of 50%. These latter two conditions would, in reality, contribute to substantial evaporation. The turbulence characteristics for neutral stability were taken from Cramer's Turbulence Classes (Cramer 1957) for rough surfaces. Wind direction was assumed perpendicular to the flight line, thus leading to maximum off-target deposit.

The results from sensitivity runs are presented in Figure 3 where the deposit (mg/m^2) is plotted as a function of downwind distance from the field edge. A light wind case of 4 km/h was chosen and the contribution to off-target deposit was examined for various spray scenarios. Four cases were modeled to look at the contribution of the aircraft WAKE, the evaporation of the spray droplets (EVP), and the atmospheric turbulence (DSP) on the drift and subsequent deposit to an off-target surface. Generally, the off-target deposit is approximately 1% of deposit within the spray block. Beyond 50 m the various contributions to drift are more apparent. Of the four cases, the one leading to the least drift is the case where no evaporation occurs (WAKE, DSP) and could be achieved by spraying during high humidities or by using a nonaqueous dilutent. The aircraft wake in moving the material closer to the target before being affected by dispersion leads to less drift beyond the edge of the field. The worse case drift and hence off-target deposit occurs when the evaporating cloud is dispensed by an aircraft with a weak vortex and is dispersed by background turbulence. The effects of varying wind speeds on off-target deposit are illustrated in Figure 4 for full model (WAKE, DISPERSION, EVAPORATION) runs. For the 4 km/h case, results for the aerial application can be compared to a ground rig application with a boom height of 1 m. The decreased deposit at the field edge from the ground rig is due to the fact that the first spray line was more than a boom width inside the field edge. However, it is apparent that the drift from the ground rig would be substantially reduced from aerial applications due to the close proximity of the boom to the ground. For the aerial application, the off-target deposit increases substantially with increasing wind speed. For winds in excess of 16 km/h, the deposit at the field edge is less with a constant deposit out to 40 m. To counteract this off-target deposit, a flight line offset could be introduced. At the higher winds, the rate of decrease of deposit with downwind distance is substantially slower (an order of magnitude/85 m) than for the light wind case (an order of magnitude/25 m). Using acute toxicity information for fingerlings (96 h LC50 of 1.3 mg/L), the surface deposit to water which is "tolerable" from an acute lethality point of view is 130 mg/m^2 assuming a mixing depth of 10 cm. With a cross wind of 16 km/h, the model indicates a required buffer zone near 85 m or 45 m if the required flight line offset was followed. Regulations in New Brunswick for the aerial application of Roundup® require a 60-m buffer zone from water. These regulations encompass spraying in winds up to a maximum of 16 km/h. The above calculations use acute toxicity information for fish and are used to provide an example of how the physical/biological interface can be made. If such a method were to be employed in a regulatory context, it would be necessary to determine an appropriate sensitive indicator on which to base the calculations.

Similar sensitivity studies for ULV forestry spraying or agricultural spraying can be modeled with the use of the PKBW or AGDISP Models. With these models, the operator can evaluate the benefits of different spray technology in ensuring maximum target coverage. On the other hand, the models can also be used by regulators to ensure adequate environmental protection in worse case spraying scenarios.

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New Directions in Servicing Climate Users

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Abstract

Climatology in the Federal Government has enjoyed a relatively long and productive life. Each year thousands of Canadians make extensive use of the climate services of the Canadian Climate Centre (CCC) in Downsview or one of the six regional offices of the Atmospheric Environment Service (AES). The climate activity in AES involves an annual expenditure of $17 million and 228 person years, roughly 8% of the total AES expenditure. An important mission of the service is to make effective and useful climate data and information available to users in a convenient and meaningful form.

Today's climate information users come from many walks of life. They come from the traditional use areas such as government, university, and engineering. However, increasingly, users from business and industry are after climate risk and design information and a few desire near real-time data and climate forecasts. Architects, attorneys, insurers, and economists are a new breed of quality users who have important climate needs. Of course, individuals with climate-related questions in health, recreation, education, and the environment are always looking for information that is easy to interpret.

Climatologists know only too well that while the types and numbers of users have swelled in the past decade, there are still many more "could be/should be" users of climatology who are largely unaware of the enormous economic and social advantages to be gained by the proper application of climate information.

Résumé

La climatologie est depuis longtemps un secteur productif du gouvernement fédéral. Chaque année, des milliers de Canadiens font un usage considérable des services du Centre climatologique canadien (CCC) de Downsview ou de l'un des six bureaux régionaux du Service de l'environnement atmosphérique (SEA). Les activités climatologiques de SEA comportent des dépenses annuelles de 17 millions de dollars et l'utilisation de 228 années-personnes, soit environ 8 % des dépenses totales du SEA. Une mission importante du Service consiste à fournir aux utilisateurs de l'information et des données climatiques utiles sous une forme pratique et significative.

Les utilisateurs actuels de l'information climatique proviennent de nombreux secteurs d'activité. Bien que les secteurs traditionnels comme le gouvernement, les universités et le génie soient bien représentés, des utilisateurs du monde des affaires et des milieux industriels se joignent de façon croissante à ceux qui désirent de l'information sur les concepts et les risques climatiques et, dans quelques cas, des prévisions climatiques et des données en temps réel. Les architectes, les avocats, les agents d'assurance et les économistes forment une catégorie d'utilisateurs de qualité qui ont d'importants besoins climatologiques. Évidemment, ceux qui demandent de l'information liée au climat dans les secteurs de la santé, des activités récréatives, de l'éducation et de l'environnement recherchent toujours des données faciles à comprendre.

Les climatologistes savent bien que, malgré l'accroissement considérable des types et du nombre d'utilisateurs au cours de la dernière décennie, il existe encore beaucoup d'autres clients potentiels qui n'ont qu'une vague idée des énormes avantages économiques et sociaux qu'on peut retirer d'un emploi judicieux des données climatiques.

Forestry-Climate Users

Lack of appreciation of the use and value of climate information is not apparent in the forestry sector; perhaps because almost every activity from establishing, growing, and protecting the forest to harvesting the trees requires an understanding of climate (Pierpoint 1980).

The appropriate type and format of climate information should vary from one application to another. However, as Silversides (1980) points out many studies appear to find simple forms of climate information quite suitable. Yet, the potential exists for increasing the effective use of climate information in forestry.

Serving the forestry-climate user is not without its problems. In 1980 at the Canadian Climate Program (CCP) forestry sector workshop, Silversides (1980) discussed problems in serving the needs of the Canadian forestry manager. It is encouraging to report that in the intervening years, progress has been made in resolving some of the data concerns and improving the service to forestry-climate users.

Of course, there is still an attitude problem among some which may never be totally eliminated. Some feel they know all there is to know. They see climate as average weather, unchanging and only one of many other, more important variables to consider. On the other hand, others feel that climate is too complex and abstract. They say there is nothing you can do about it, you are already locked in. Still others question the value, cost, and availability of the information.

Differences in data format have caused difficulties in the past. Fortunately, the CCP, new technology, and a greater appreciation of user requirements have resolved many of the information problems. However, AES is a national weather service with responsibility for serving a multitude of users with incredibly diverse and imaginative data/information needs. It has been suggested that AES has too many products and, where possible, they should be reduced in numbers, simplified and standardized (DPA Group 1985). Users of information must be more flexible and reasonable in what they expect from AES.

One persistent complaint is that the coverage of climate data is too sparse. Comparisons with other countries show that Canada's precipitation network of about 2700 stations or 2.6 gauges per 10 000 km² is about the same number of stations as in Iran, but is a smaller density than that of Ethiopia or Algeria. Realistically, our station density is unlikely to change. It is doubtful whether governments will ever approve sufficient monies to pay for the costs of installing, equipping, maintaining stations, and archiving the data from a sizable expansion of the basic climate network. Consequently, one must examine other possibilities, which may be more cost effective, for providing better climate information to users. Such opportunities exist, but have not yet been exploited. They are associated with greater use of proxy data sources, with improvements in the acquisition and management of climate observations from provincial and local networks, with developments in remotely sensed data collection and transmission, and with computerized analytical techniques (Phillips 1986b).

Another common complaint from foresters is that most climate stations are not representative of the forest setting. There is no immediate solution to this problem either, although improved analysis techniques, good research, and more remotely sensed observing platforms should help.

Other problems are missing data, gaps in the record, and multiple, undocumented changes in station location. Many persons are concerned with data record problems. I can only hope that progress made in the last 5 yr in solving the earlier data problems augers well for solving the missing data problems. Interest in climate change issues and the need for long-term homogeneous records offer real incentives for improving data completeness.

Climate Services and Products

The growing number of major, quality climate information users demand that climatologists provide many different data sets and information that are convenient, high quality, meaningful, digestible, and transferable.

The types of services requested and provided range from answering specific data requests over the telephone to personal consultation with the client on what data sources, summaries, and reports are available and most applicable to the client's specific problem. A full spectrum of products and services from historical time series analysis to the monitoring and prediction of climate anomalies now and into next season could be made available and attractive to users.

Risk and Design Data

Climate risk and design data are published in a variety of media including data periodicals, atlases, and interpretive studies. Wherever possible the presentation is in a form easily intelligible to the user, for example, extreme value statistics, frequency analysis or a "straight" probability statement.

"Now" Information

A new category of climate information is the monitoring of in-season or current conditions. Such information involves not only the year-to-date accumulations (heating degree-day totals, seasonal snowfall), but also the "now-only" conditions (e.g. mid-July soil moisture, late April soil temperature).

Climate Forecasts

Climate forecasts for a month or a season ahead are generally the product most eagerly desired by the public. At the Canadian Climate Centre, an experimental monthly and seasonal climate prediction project began in 1985 (Shabbar 1985).

To date, on the average and nationwide, monthly temperature forecasts show marginal skill, but precipitation forecasts show no skill. Seasonal forecasts also demonstrate no skill. There is some exceptional regional skill in the monthly forecasts, although until larger samples are taken, we must assume the skill results from fortuitous sampling variations. Experimental forecasts will continue until July 1987 with the earliest public distribution of climate forecasts in late 1987.

Consultation

Climate services like forecast services are available to the general public as well as to government, commerce, and the professions. The AES has several free brochures, fact sheets, and circulars that are sent out on request. In addition, there are hundreds of booklets or publications on various aspects of Canada's climate that are available at reasonable cost from Federal Government publishing centers, from AES regional offices, or the CCC in Downsview. The service also offers a consultancy service. When investigative work or discussion with a client takes an appreciable amount of time or consumes any materials or supplies, a charge is normally made.

Climate Archival Forms

The AES receives many different data sets and formats, for many different parameters, on many different scales (time and space), and for many stations. Data are stored in digital, paper, and micrographic form.

Climate Data in Digital Form

Today the CCC has more than 275 magnetic tapes (6250 bpi) which contain 2.5 billion weather observations. There are different archive data sets corresponding to different observing frequencies, for example, 15 min, hourly, daily, or monthly; and element types, for example, wind speed, visibility, total rainfall.

Detailed format documentation is available on request. Archive copy can be supplied on nine-track magnetic tape with characteristics suited to the user's computer system. Data can also be copied to flexible diskette for use with personal computers at the user's own work location. Generally, one diskette can hold complete data sets of four elements of daily data for one station with approximately 75 yr of record (Carr 1986). Numerous software packages are available to access archived data and to provide listings and statistical analysis in report form to meet user's needs (Webb 1980).

A copy of the data retained in the National Climatological Archive or tailored statistical analyses can be obtained by contacting the Canadian Climate Centre or any AES regional office. Users may also apply to the CCC to open an account permitting direct access to the digital archive and support programs. All data analysis or copies prepared for clients are on a cost-recovery basis with cost estimates prepared on request.

Climate Data in Published Form

Each month AES receives forms for archiving and publishing from some 3000 stations. The published or paper section of the National Climatological Archive has more than 15 million original weather documents (observing forms) from about 5000 stations covering their entire period of operation, in some instances back to the mid-19th century. It also contains nearly 2500 titles of published works on Canada's climate.

Periodicals are issued weekly, monthly, and seasonally and special statistical publications and interpretive studies are issued occasionally. Most publications are printed although micropublishing is becoming an increasingly more popular and efficient means of publishing data periodicals.

In addition, each year there are monographs of specialized studies dealing, for example, with the impact of climate on the country's forests, its tourism and recreation activities, its transportation, the climate of Canada or one of its regions, cities, etc.

Climate Data in Micrographic Form

The micrographic section of the National Climatological Archive consists of over 10 000 microfiche and 12 000 reels of microfilm. Included are original observing forms and charts from about the mid-1800s, surface weather maps from 1872, upper air charts from 1957 and ice reconnaissance maps from 1959.

The microfiche library also contains long-term abstracts of hourly, daily, and monthly temperature and precipitation data, radiation, degree-days, and wind, all to 1980 organized chronologically by station. These fiche are updated every 5 yr.

Emerging Issues

The business of servicing users with climate information is anything but static. Increasingly, there are more demands for climate information in a variety of formats and media from an increasing spectrum of users. At the same time, one is confronted with new issues — some seemingly contradictory such as privatization and revenue generation, some foreign such as marketing, and others long-standing such as shrinking and changing data networks. Ongoing issues that must constantly be addressed are changing user requirements, new technology, and improved scientific and statistical methodologies.

Privatization

The Federal Government is committed to the development of a viable private sector in climate consultation. The Neilsen Task Force recommended that the government identify the level, potential capability, and type of activities that could be undertaken by private industry; determine the realistic data service costs to external users; consider the regional impacts of privatization; and generally encourage the development of the private sector by contracting-out.

The AES is committed to encourage the private sector to take over the provisions of all services that fall outside the AES basic level of service. To clarify the role of private meteorology, AES is defining exactly what the service will or will not do and what specific services it will provide to sectors such as forestry (Atmospheric Environment Service 1986).

Revenue Generation

Increasing demands for services necessitate that we cannot do everything for everyone for nothing. Also, it is necessary to apply a realistic and uniform level of charges for climate-related services to avoid undercutting private sector meteorology.

Marketing

Climatologists are not ones to market the use and value of their products. Instead, they have left it to the user to come calling and to provide testimonials about the economic usefulness of climate information. In today's decision arena there is an incredible amount of available information. Climatologists must compete with other information suppliers for the user's time and therefore must aggressively begin to market saleable climate information. Good marketing involves several characteristics including knowing the market; developing saleable products or services; packaging convenient, timely, and useful information; distributing information to places of decision making; and promoting services as a need, not a want. For a full treatment of marketing climatology see Phillips (1986a).

New Developments in Servicing Climate Users

Computer and Communications Technology

Climatology is a developing science and one much affected by technological advances. Computer and communications technologies are expected to play an ever-increasing role. Large capacity mass storage devices such as optical disk storage present enormous potential for the effective dissemination of climatological data and information. Radar and satellite sensing techniques are, of course, widely used for general forecasting purposes. These data in their original digital forms represent a valuable asset with significant application potential in climatology. Currently, the CCC has a satellite data archiving system that receives, reduces, and archives visual and IR images every 3 h (Y. Durocher, pers. comm.).

Apparently the requirement and demand for paper publications will remain for some time. However, there is the potential for reducing the printing costs of publications by also producing them in digital form on some mass storage medium or printing individual copies on demand using laser print technology.

Climate Analysis Software

A new form of climate analysis has emerged with the development of user friendly, interactive, menu-driven applications software. Analysis packages such as MAST or LAST that can run on microcomputers can produce tabular, graphical, and chart-form summaries of climatological information to a much wider community (Saulesleja et al. 1985).

Objectively Analyzed Data

One major new thrust within the CCC will be to archive and make use of objectively analyzed databases. Such systems will permit better integration of conventional observations and remotely sensed data, and permit the more accurate determination of the temporal and spatial variation of climate parameters.

Climate Data Management Systems

A major CCC project to develop a modern software system, the Climate Data Management System (CDMS), will be completed by 1987 (Durocher 1986). The on-line database management system will improve timeliness of data capture, control of documents, modern quality control procedures, and the ease of data access, thus enabling all users to obtain the climate data they need when they need it.

All stations for which data are stored in the AES National Climatological Archive will be fully described in the Station Information System (SIS). In addition, non-AES station histories will also be entered into SIS to the extent their information is provided to AES. SIS will also contain information about foreign stations as required. The main feature of SIS is its query capabilities and facility for information display and reports. It will not, however, contain any climatological data.

An important aspect of the CDMS is to increase convenient and inexpensive user access to the digital archive and inventory of climatological data. Anyone who has an account may have access to the AS9 and the digital archive for either data retrieval or analyses, for a nominal computer charge. On-line systems are being used by our regional offices and by several paying customers.

Conclusion

Climatologists serving users face many challenges. There is always the challenge to generate good climate information that is relevant and transferable. Also important is delivering information into the user's hands, efficiently and effectively. Another challenge is to listen to users to ensure that the services supplied are needed and that users can use the information effectively. These challenges will require adaptability to new technology.

Through the use of more creative forms of climatological information, more imaginative presentations, and increased user contacts and services, Canadian climatology will continue to grow to meet the future needs of Canadians.

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POSTER PRESENTATIONS

Poster Presentations

I am pleased to have been involved in Forest Climate '86 with the theme of "Climate and Its Role in Forest Renewal and Production."

The posters provided an excellent opportunity for dialogue on new developments and recent directions in forestry, and climatic techniques and products, with specific relevance to climate and its role in forest renewal and production. A total of 17 posters were presented ranging from selfexplanatory to hands-on computer demonstrations and posters.

I wish to thank all individuals involved in the poster presentations for their cooperation and contribution to the success of Forest Climate '86.

Stephen J. Masarovich
Poster Session Chairman

Role of the Early-Morning Convective Boundary Layer in Forest Spray Operations

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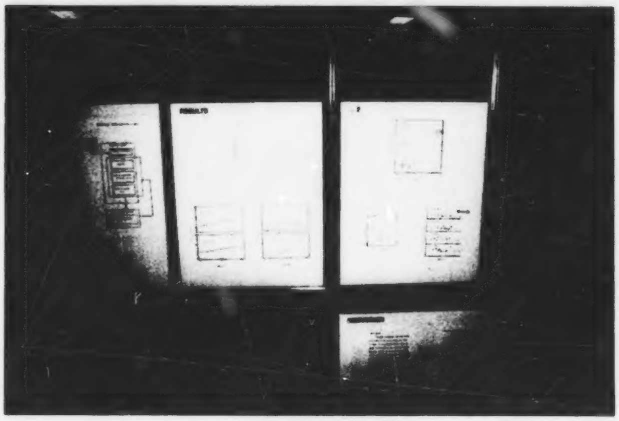

Abstract

The growth of a convective boundary layer during the postdawn period plays a significant role in aerial spraying of forests. Both the depth of this layer and the intensity of the turbulence within it exert a profound influence on the deposition and drift of the spray. This poster presentation considers a simple computer model that was developed to simulate (1) the growth of the convective boundary layer and (2) the associated changes in the above-canopy turbulence intensities. The model is validated against field data from the 1983 and 1984 Dunphy spray trials, conducted in central New Brunswick.

Résumé

La couche limite convective qui se forme après l'aube joue un rôle important dans la pulvérisation aérienne effectuée au-dessus des forêts. L'épaisseur de cette couche et l'intensité de la turbulence qu'on y observe ont un effet majeur sur le dépôt et la dérive des bruines. Cette présentation au moyen d'affiches examine un modèle informatique simple qui a été conçu pour simuler la formation de la couche limite convective et les modifications connexes de l'intensité de la turbulence au-dessus du couvert forestier. La validité du modèle est confirmée par des données recueillies sur le terrain au cours des essais de pulvérisation de Dunphy, effectués dans le centre du Nouveau-Brunswick en 1983 et 1984.

Although aerial spraying of insecticides to control forest insects has been regularly used in Canada for many years, many questions regarding the impact of insecticides on the environment or public health still remain unanswered. Because of this increase in the concern about the effect of insecticides on nontargeted organisms, there is a major need to quantify the impact of such releases. The many inherent complexities associated with aerial applications of insecticide prevent a comprehensive description of the problem.

Deposition of insecticides onto a forest surface is a difficult process to control. Enlarging the size of the spray droplet would certainly facilitate the control of deposition (and drift) by increasing the settling characteristics of the spray droplets. However, the end result in terms of both cost and insect mortality (Himel and Moore 1969) does not support the use of such droplet sizes. To avoid localized deposition and to increase the overall effectiveness of the spray, the use of ultra-low volume (ULV) spray droplets is warranted. Ultra-low volume spray droplets, because of their smaller inertial masses and sedimentation velocities, are generally more prone to the influences of the atmosphere.

Historically, aerial forest insecticide spray applications in Canada have been performed largely in stable atmospheric conditions, during the early morning and evening periods, in an attempt to minimize off-target drift (Crabbe et al. 1984). The practice, particularly in highly stable situations, can encourage not only greater wind drifting, but also reduced on-target deposition.

The initial downward delivery of the ULV spray is greatly enhanced by the descending vortex structures shed by the spraying aircraft. Because of the spray's fine composition, the bulk of the material released from the spray aircraft is entrained by the vortices. The effective transport capability of the system before impaction on the forest canopy is a function of the aircraft's altitude above the canopy and the intensity of background turbulence. Given extreme conditions of turbulence, the vortex structures quickly lose their integrity, resulting in the release of the insecticide to the atmosphere.

In stable atmospheric conditions, where ambient turbulence is minimal, the vortices generated by the spray aircraft persist for an extended period of time, potentially exposing a substantial amount of the spray material to wind transport. In such situations, very little of the entrained material actually gets deposited in the intended zone of application. For decreasing stabilities, where the effects of stability promote greater vertical motion, the influences of the mean wind on the vortices become less important.

In unstable atmospheric conditions, the insecticide can further be prevented from reaching the intended forest target through vortex breakdown — the gradual erosion of the vortex system by background turbulence — and through the ensuing vertical dispersion and drifting of the spray cloud.

Clearly, to minimize the effects of atmospheric stability on deposition and drift requires that the spray aircraft fly very close to the top of the forest to inject the vortices (and insecticide) directly into the canopy, thus leaving little time for the vortices to be acted on by the local turbulence and wind field. Certainly, in principle, the inherent dangers associated with the practice of low flying negate the implementation of such measures in field operations.

In unstable conditions, however, the presence of an elevated stable layer aloft (i.e., above the spray aircraft) in the early morning can help minimize the effects of vortex breakdown, vertical dispersion, and subsequent wind drifting by confining the airborne insecticide to the underlying convective layer. In recent years, field studies have revealed that with increasing turbulent activity in the layer, droplet penetration into a forest canopy increases, decreasing the overall amount of insecticide available to wind transport (Crabbe et al. 1984).

Effectively, the degree of deposition and drift is a function of the height of the convective layer and the vigor of mixing in that layer. Generally, the shallow layers achieve the more desirable results.

The growth of the convective boundary layer through the stable layer aloft is a function of insolation at the canopy surface. The convective layer is said to be unconfined whenever the layer breaks through the stable layer aloft. This generally takes 3–4 h after the initial rising of the sun. In principle, deposition is optimal for only several hours during the early morning period, leaving little time for a forest manager to carry through with an effective spray program. The forest manager, however, has available a means of minimizing drift near highly sensitive areas (e.g., along streams and lakes, and near habitation).

Pesticide drift and deposition models presently available to forest managers as an aid in their decision making do not incorporate the effects of the changing convective boundary layer in their treatment of drift. To enable a more accurate representation of drift, and thus deposition, especially during the early morning, it is recommended that the treatment of the convective boundary layer be included in the models.

A simple model to simulate the growth of the early-morning convective boundary layer and associated changes in the turbulent fluxes is presented. A conceptual representation of the integrated model is given in Figure 1. A comparison of the results of the predictive model against field data from the 1983 and 1984 New Brunswick Dunphy experimental spray trials (Crabbe et al. 1984, Mickle et al. 1984, Crabbe and McCooeye 1985) is also presented.

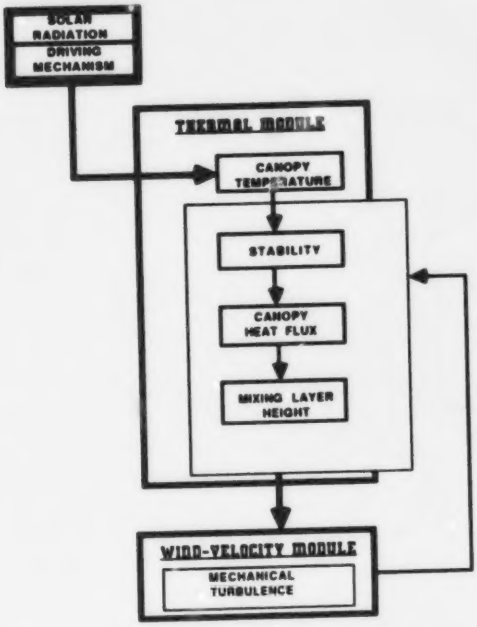

FIG. 1. A conceptual representation of the simulation model.

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Provisional Site Regions of Eastern North America: Effect of Macroclimate on Tree Species-Site Relationships

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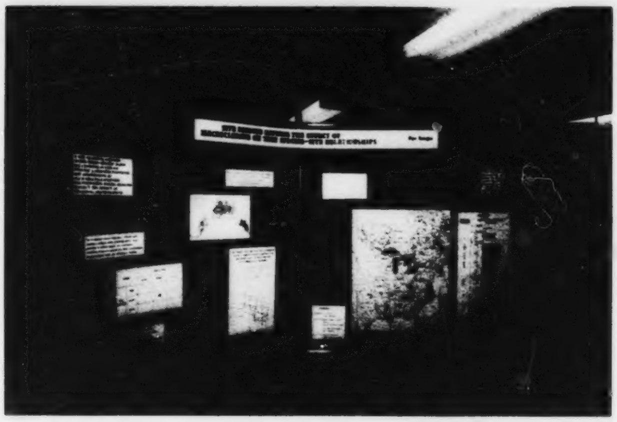
Ministry of Natural Resources, Maple, Ontario



A site region is a region within which specific plant successions occur on specific landform positions. Gradients in (regional) macroclimate cause differences in relationships between tree species and site.

For comparing such relationships within and among regions, a matrix of nine physiographic sites is used as a stable basis; two important site factors, air temperature regime and soil moisture regime, provide the axes (Fig. 1). These nine physiographic reference sites are related to landform positions. The "normal-normal" site (x) refers specifically to a deep loam soil with a gently undulating relief which imparts no extreme influence on local climate. Other combinations of soil and relief result in drier, wetter, hotter, and colder than normal sites.

Tree species tend to prefer different land form positions in different site regions, for example, along a continental temperature gradient from subarctic Ontario to low warm temperate Alabama as is illustrated for five species occurring on sites with normal moisture and three different local climates (Fig. 2).

A key reference for the characterization of site regions is the most stable (climax) forest on the "normal-normal" site; climatic information provides valuable additional support.

Site regions have been described and mapped for Ontario (G.A. Hills 1945-61) and somewhat revised (D. Burger 1986). That regional concept has served to develop a map for all of Canada (Subcomm. Climatic Ecoregions of Canada, Canada Comm. on Ecological [Biophysical] Land Classification, manuscript, 1986). Similar work to complete coverage of eastern North America is in progress (D. Burger 1976-86). The map of Provisional Site Regions of Eastern North America (Fig. 3) has symbols (Fig. 4) similar to those on the Canadian map.

MATRIX		TEMPERATURE		
		HOTTER	NORMAL	COLDER
SOIL MOISTURE	DRIER			
	NORMAL		X	
	WETTER			

FIG. 1.

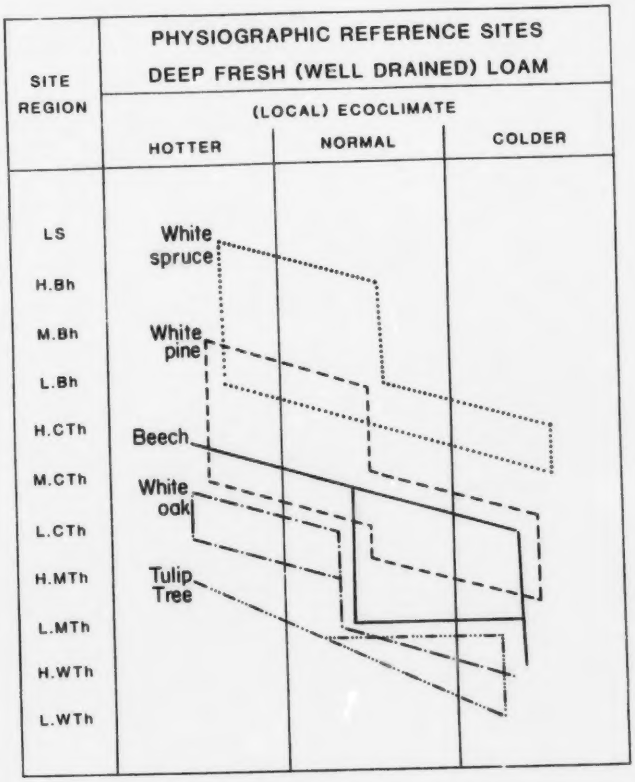

SITE REGION
PHYSIOGRAPHIC REFERENCE SITES
DEEP FRESH (WELL DRAINED) LOAM
(LOCAL) ECOCLIMATE
HOTTER
NORMAL
COLDER
LS
H.Bh
M.Bh
L.Bh
H.CTh
M.CTh
L.CTh
H.MTh
L.MTh
H.WTh
L.WTh
White spruce
White pine
Beech
White oak
Tulip Tree

FIG. 2.

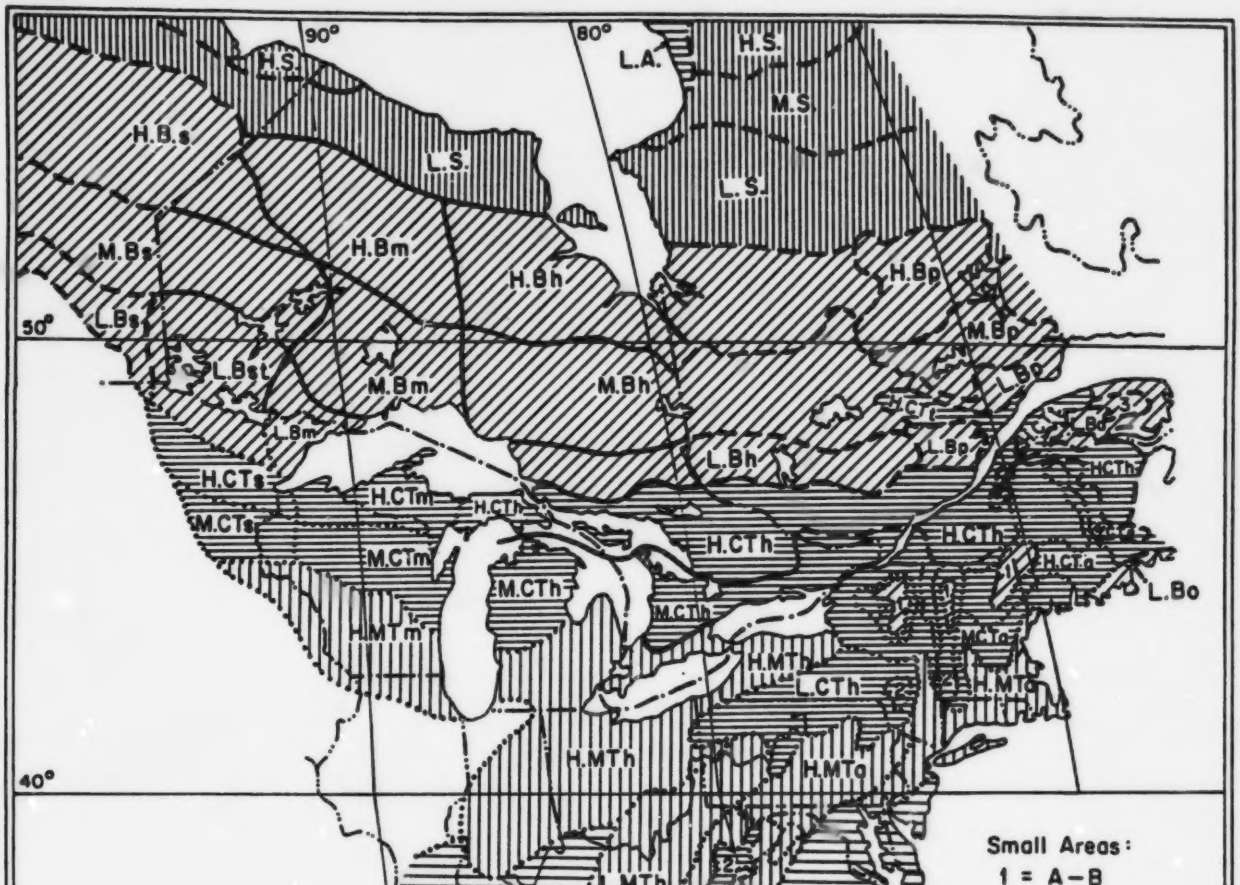

90°
80°
50°
40°
30°
H.S.
L.A.
M.S.
L.S.
H.B.s
M.Bs
L.Bs
H.Bm
H.Bh
H.Bp
M.Bp
L.Bp
L.Bst
M.Bm
M.Bh
L.Bm
L.Bh
CT
H.CTs
M.CTs
H.CTm
H.CTh
M.CTm
M.CTh
H.CTa
M.CTa
L.Bo
H.MTm
H.MTh
L.CTh
H.MTa
L.MTh
H.WTh
H.WTa
H.MTa
H.ST
LWTh
L.ST
Small Areas:
1 = A-B
2 = A-CT
3 = L.Bp
0
500
Kilometers
Site Regions (Ontario)
Climatic Ecoregions (Canada)
Site Regions (eastern USA)
D. Burger, 1986.

FIG. 3. Provisional site regions, eastern North America.

LEGEND

ONTARIO SYMBOLS	CONTINENTAL SYMBOLS (Tentative)	
	A = ARCTIC	
	L.A	Low ARCTIC
	S = SUBARCTIC	
	H.S	High SUBARCTIC
	M.S	Mid SUBARCTIC
1E	L.S	Low SUBARCTIC
	B = BOREAL	
2S	H.Bs	High BOREAL sub humid
2W	m	High BOREAL mod.humid
2E	h	High BOREAL high humid
	p	High BOREAL per humid
3S	M.Bs	Mid BOREAL sub humid
3W	m	Mid BOREAL mod.humid
3E	h	Mid BOREAL high humid
	p	Mid BOREAL per humid
4S	L.Bs	Low BOREAL sub humid
4W	m	Low BOREAL mod.humid
4E	h	Low BOREAL high humid
	a	Low BOREAL atlantic
	p	Low BOREAL per humid
	A.B	Mountain BOREAL (Altitudinal)
	CT = COOL TEMPERATE	
5W	H.CTm	High COOL TEMP. mod. humid
5E	h	High COOL TEMP. high humid
	t	High COOL TEMP. transition
	a	High COOL TEMP. atlantic
	M.CTs	Mid COOL TEMP. sub humid
	m	Mid COOL TEMP. mod. humid
6E	h	Mid COOL TEMP. high humid
	a	Mid COOL TEMP. atlantic
	L.CTh	Low COOL TEMP. high humid
	A.CT	Mountain COOL TEMP. (Altitudinal)
	MT = MODERATE TEMPERATE	
	H.MTm	High MOD. TEMP. mod. humid
7E	h	High MOD. TEMP. high humid
	a	High MOD. TEMP. atlantic
	M.MTa	Mid MOD. TEMP. atlantic
	L.MTh	Low MOD. TEMP. high humid
	A.MT	Mountain MOD. TEMP. (Altitudinal)
	WT = WARM TEMPERATE	
	H.WTh	High WARM TEMP. high humid
	a	High WARM TEMP. atlantic
	L.WTh	Low WARM TEMP. high humid
	ST = SUBTROPICAL	
	H.ST	High SUB TROP.
	L.ST	Low SUB TROP.
	T = TROPICAL	

FIG. 4. For forest practices, a site region is an area in which similar responses may be expected from similar practices within similar combinations of forest type and physiographic site type. It is hoped that site regions will be useful to forestry and land management when developing opportunities and recognizing limitations in the transfer of knowledge and of plant materials.

Energy Plantation Research in Newfoundland

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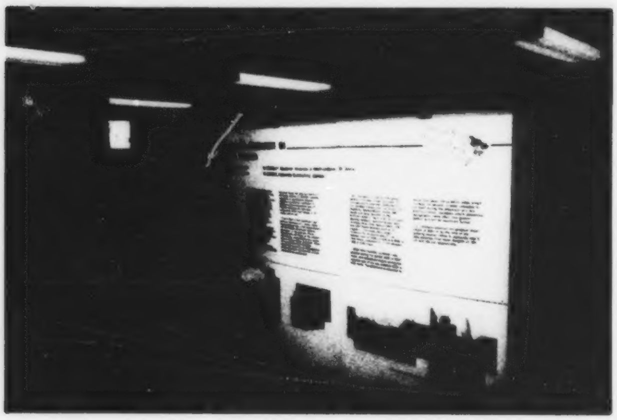

Abstract

In Newfoundland, research to evaluate *Salix* spp. for agroforestry and community shelterbelts began in 1981. More than 150 clones were acquired from local and international sources and evaluated in nursery trails. Since the inception of the project, collaboration has been close with Long Ashton Research Station, Bristol, England, and the Swedish University of Agricultural Sciences, Uppsala, Sweden, and other institutions for supply of *Salix* clones.

Résumé

On a entrepris à Terre-Neuve en 1981 des travaux de recherche visant à évaluer *Salix* spp. comme rideau-abri à des fins agroforestières et communautaires. Plus de 150 clones ont été obtenus de sources locales et internationales et évalués en pépinière orestière. Depuis le début du projet, on a collaboré étroitement avec la station de recherche Long Ashton de Bristol, en Angleterre, ainsi qu'avec l'Université de sciences agricoles de Suède, à Uppsala, et d'autres institutions à des fins d'approvisionnement en clones de *Salix*.

In 1982, ENFOR (ENergy From the FORest), a contract program administered by the Canadian Forestry Service, began funding the energy plantation aspect of the project.

In 1983 the work was broadened to reflect the full scope of research and development necessary for establishing economically viable plantations. A greater emphasis was placed on biogeographical and biometeorological studies to ensure optimum clone-site matching. The collection of microclimatological data from potential plantation sites increases our understanding of the environmental conditions that control plant growth.

Initial results from 4-yr-old experimental plots at the Pasadena nursery show an exceptionally high production rate for *Salix elegantissina* (Table 1). However, indications are that production rates of 11–15 t of dry matter per hectare per year are more realistic with other selected species, planted on the best sites and grown on 3-yr rotations.

Large-scale plantations were established on four cleared productive forest sites in central and eastern Newfoundland during 1985 and 1986 to determine the economic viability of growing energy plantations.

Climatological studies provide a basic understanding of the radiation and energy balances of plantation sites, and are integral to matching clone and site. To this end, a portable battery-powered energy balance measurement system has been developed and was field tested in 1985. This device, an RTDMS (Reversing Temperature Difference Measurement System), measures the Bowen ratio using psychrometry and a vertical interchange apparatus for sensors. In association with independent measurements of net radiation, soil, and biomass heat storage, the energy balance of the surface is solved. An advanced field datalogger is used to collect the data as well as control the timing of the interchange of the psychrometers.

In support of the field system three analysis programs are available: 1) ENBAL calculates hourly and daily summaries of the energy balance, 2) RADBAL provides summaries of the radiation balance, including the reflection coefficient of radiative surface temperature, and 3) STORAG calculates the individual components of the heat storage of the canopy and the soil.

In June 1986, a field experiment was started at Glenwood on a newly cleared future plantation site. Initial measurements with the RTDMS will provide baseline information

TABLE 1. Dry matter weight estimations for 3-yr-old *Salix* clones at Pasadena, Newfoundland, based on test plots planted at 25 000 stems per hectare.

Species	25 000 Stems/ha (t/ha/yr)	35 000 Stems/ha (t/ha/yr)	Mean height (cm)
S.elegantissina	27	38	475
S.alba	11	15	446
S.fragilis	9	13	404
S.triandra	8	12	388
S.viminalis	8	11	398
S.nigra	2	3	318

on the bare soil. Future measurements will focus on the radiative and energetic characteristics of a willow stand at various stages of growth. These will be correlated with biological productivity to provide an understanding of the interactions between the various clones and the environment.

An investigation of the diurnal growth patterns of clones of *Salix purpurea, S.viminalis,* and *S.alba* was conducted at the Canadian Forestry Service nursery at Pasadena during 1985. Height and base diameter of the dominant shoot of each of 90 (30 of each species) randomly selected stools were recorded three times daily at 0600, 1400, and 2200 h between June 20 and August 17. The mean daily height increment increase for all shoots was 0.7 cm between each of 2200 to 0600 and 0600 to 1400 h, compared with 1.3 cm between 1400 and 2200 h.

Mean daily diameter increment growth was greatest during the period of 2200 to 0600 h, and decreased slightly between 0600 and 1400 h. The difference is assumed to result from lower transpiration rates during the night which increase the amount of water available to the plant. Climatic variables which determine transpiration rates will possibly affect this growth pattern and are being investigated in further analysis of the data.

Salix viminalis attained the greatest mean height of 208 cm by the end of the growing season, while *S.purpurea* and *S.alba* obtained final mean heights of 185 cm and 180 cm, respectively.

Recent Tree-Line Drop in Eastern Newfoundland

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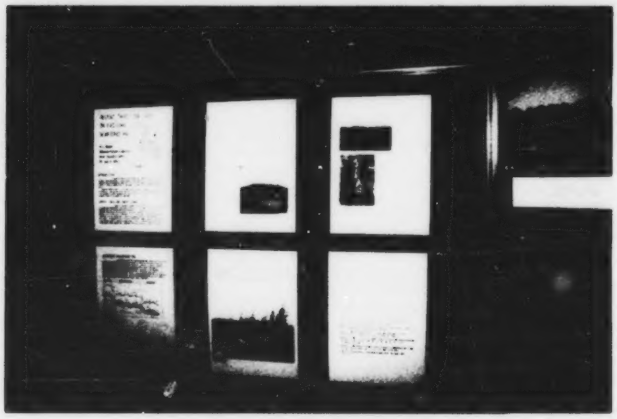

Abstract

Heathlands dominated by ericaceous dwarf-shrubs cover 2.0 million ha or 20% of insular Newfoundland. Although balsam fir and black spruce once grew on these sites, past experience with afforestation has identified site selection regarding climatic exposure to be a critical element in plantation survival and growth (Lewis 1954, Nickerson 1969, Wilton 1970, Hall 1986).

Nickerson (1968) attempted to use exposure flags to assess the climatic suitability of heaths for afforestation. Vandalism prevented calibration of flag tatter with site exposure for most plantations. The successional status of heath types has been documented using vegetation classification and landscape reconstruction (Meades 1973, 1983, 1986).

Résumé

La lande où dominent les arbustes nains de la famille des éricacées couvrent 2 millions d'hectares, soit 20 % de la superficie de l'île de Terre-Neuve. Bien que le sapin baumier et l'épinette noire aient autrefois garni ces terres, des expériences antérieures de création de forêts dans ces secteurs ont permis d'établir que la sélection du terrain en fonction de l'exposition aux facteurs climatiques était un élément crucial dans la survie et la croissance des plantations (Lewis, 1954; Nickerson, 1969; Wilton, 1970; Hall, 1986).

Nickerson (1968) a tenté d'utiliser des drapeaux d'exposition pour évaluer les conditions climatiques propices des landes à la création de forêts. À cause du vandalisme, il a été impossible d'étalonner les lambeaux de drapeau en fonction de l'exposition du terrain pour la plupart des plantations. Les stades de succession des types de lande ont été étudiés à l'aide de la classification végétale et des données de reconstruction du paysage (Meades, 1973, 1983 et 1986).

Heath Types and Successional Status

Figure 1 illustrates the general distribution of heath types in Newfoundland. The ALPINE HEATH and MOSS HEATH have strong floristic affinity to climatic heaths elsewhere. The SERPENTINE HEATH and LIMESTONE HEATH types are edaphic. The KALMIA HEATH occurs within forested landscapes where repeated burning and cutting have caused succession to dwarf shrub thicket. Analysis of tree invasion in the KALMIA HEATH–boreal forest ecotone confirmed these heaths have considerable stability (Meades 1986). However, the successional status of the EMPETRUM HEATH is more complex. Physiognomically and floristically, these heaths resemble subarctic tundra. The krummholz growth of conifers on these sites suggests these heaths are climatic in successional status (Meades 1973). However, subsequent observations demonstrated that this conclusion was erroneous.

The Historical Forest Limit

Figure 2A shows the location of a ridge 250–300 m in elevation on the eastern Avalon Peninsula which before 1975 was dominated by EMPETRUM HEATH. A small stand of balsam fir krummholz less than 2.0 m high, burnt during the 1975 fire, was found on top of this ridge (Fig. 2B). This stand clearly suggests the site is beyond the productive forest limit. However, the same fire also exposed many large undecomposed (relic trees) under the humus of the EMPETRUM HEATH (Fig. 3A). The average growth for the relic trees compares favorably with extant tree growth at lower elevations (Fig. 3B).

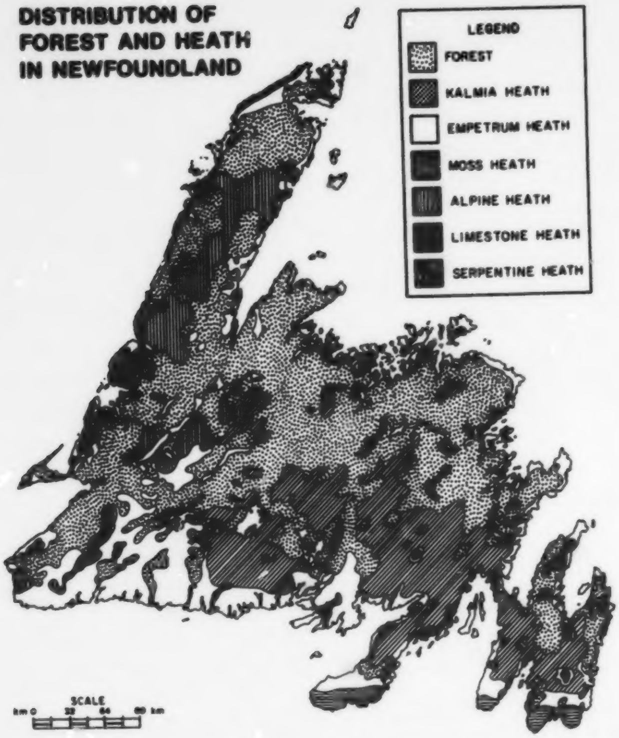
DISTRIBUTION OF FOREST AND HEATH IN NEWFOUNDLAND
LEGEND
FOREST
KALMIA HEATH
EMPETRUM HEATH
MOSS HEATH
ALPINE HEATH
LIMESTONE HEATH
SERPENTINE HEATH
SCALE

FIG. 1. Distribution of forest and heathland types in Newfoundland.

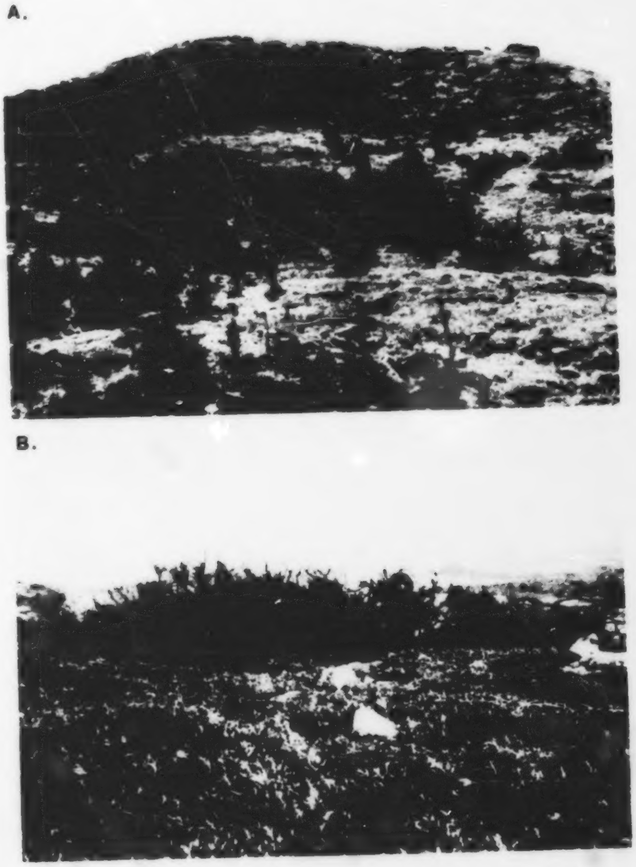

FIG. 2. A) Location of the study area above 260-m contour 30 km west of St. John's, Nfld. B) Burnt krummholz with dominant height of 2.0 m on summit of ridge.

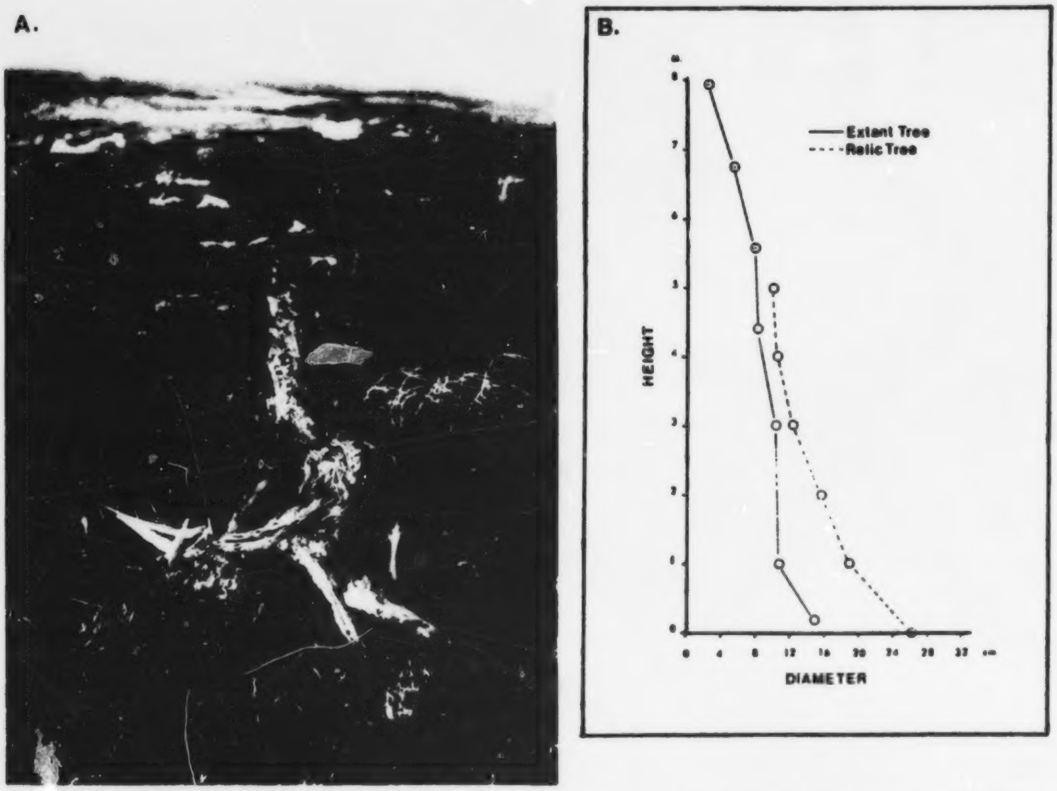

FIG. 3. A) The remains of relic trees exposed by a fire along the ridge summit in July 1975. B) The diameter-height relationship of relic trees compared with extant trees growing at lower elevations in eastern Newfoundland.

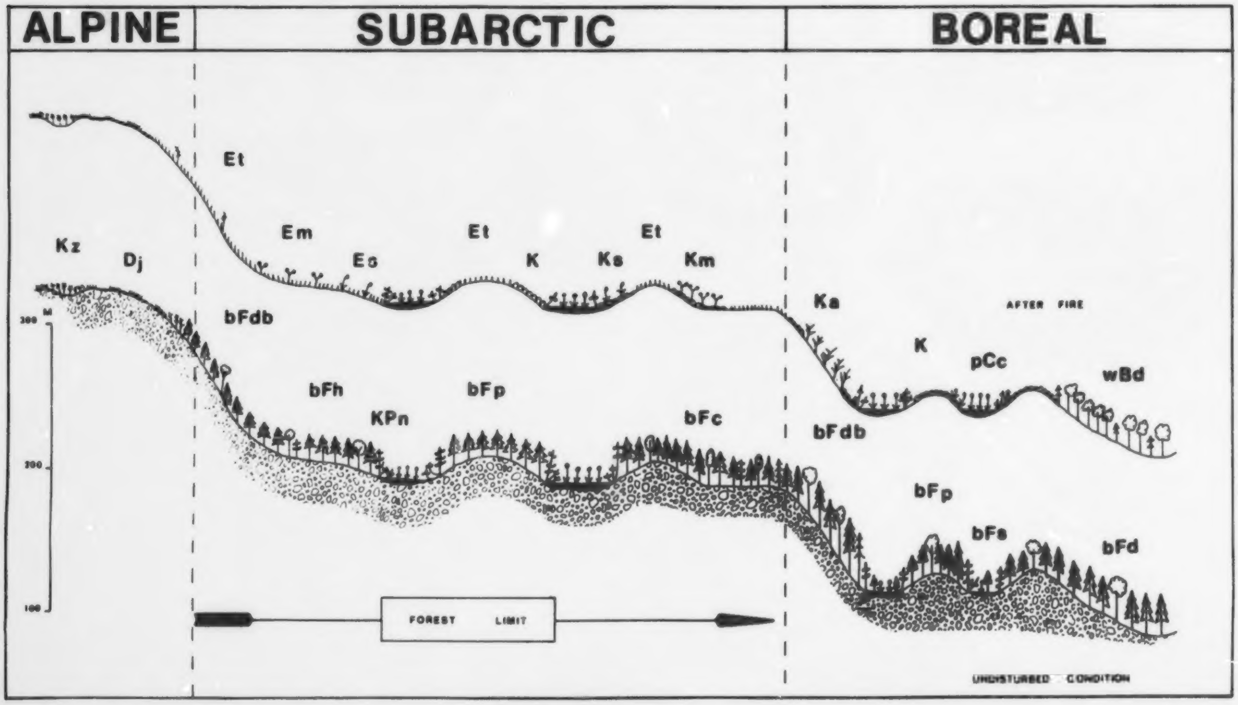
ALPINE
SUBARCTIC
BOREAL
Et
Kz
Dj
Em
Es
Et
K
Ks
Et
Km
Ka
AFTER FIRE
K
pCc
wBd
300 M
bFdb
bFh
bFp
KPn
bFc
bFdb
200
bFp
bFs
bFd
100
FOREST LIMIT
UNDISTURBED CONDITION

FIG. 4. Topographic sequence of forest types and heath types from the Alpine Zone to Boreal Zone before and after the widespread destruction of the forest limit by anthropogenic fires.

Landscape Reconstruction

On the basis of the above observations and more in-depth study of the natural vegetation–soil catenary relationships in the region, the historical relationship between the forest and heath landscapes was reconstructed (Fig. 4). There are two possible explanations for the observed drop in the forest limit: (1) There has been a general deterioration of the regional climate coincident with widespread anthropogenic destruction of the landscape. (2) The tree-line drop is due solely to the destruction of the regional forest and the climatic impact was limited to the boundary layer. Climatic evidence does not support the first hypothesis (Banfield 1983), and afforestation experiments conducted by the Canadian Forestry Service in 1966–67 support the conclusion that the drop in the forest limit is reversible.

The Future Landscape

Figure 5 shows a 20-yr-old tamarack (*Larix laricina* (Du Roi) K. Koch) plantation established on an EMPETRUM HEATH near Come-by-Chance, Newfoundland. The lee side of this plantation has already succeeded to a KALMIA-MYRICA HEATH presumably because of the deeper snow cover within 30 m of the stand edge. Interestingly, mature tamarack individuals established naturally in the heath have acquired a krummholz form less than 2.0 m high after 20 yr. This strongly suggests that individual trees in the heath do not reflect the true potential growth that can be sustained by a developing closely spaced plantation. However, species selection relative to site conditions is also critical since black spruce and sitka spruce planted on the same areas have decidedly failed with heights less than 1.0 m in 20 yr.

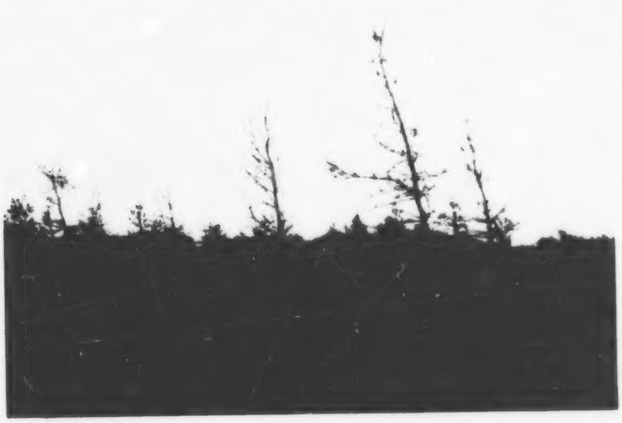

FIG. 5. A 20-yr-old tamarack plantation growing on an exposed ridge near Come-by-Chance, Newfoundland, demonstrates that historic forest limits can be regained by careful matching of species with sites.

Conclusions

1. The productive forest limit in eastern Newfoundland dropped from approximately 275-m elevation to 215 m due to widespread repeated disturbance by fire and cutting.

2. The growth form of individual residual trees in the heath cannot be used to interpret past history or to predict future potential for forest growth. Considering climate, the plantation has properties over and above the component trees.

3. EMPETRUM HEATH can produce merchantable plantations even though residual trees in these heaths have krummholz growth forms. Although there is an apparent tree-line drop in this region, it is possible to rectify the problem through afforestation.

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Albedo of a Mature Mixed Forest and a Clear-Cut Site in Petawawa, Ontario: Diurnal and Seasonal Patterns

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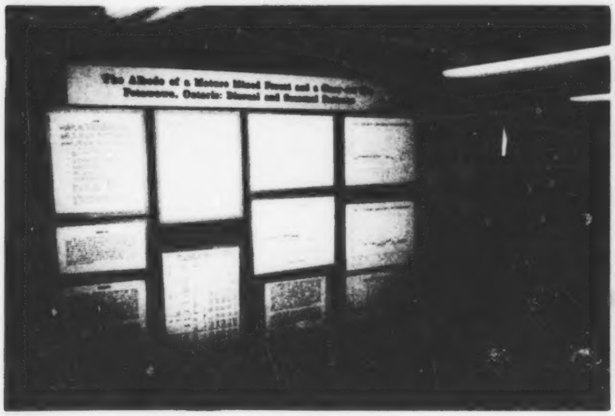

Abstract

The results of a long-term study (1981–85) of the albedo (α) of a mature forest and a clear-cut site are presented, and the diurnal and seasonal patterns are reported.

The forest is a mixed stand of coniferous and deciduous species. The clear-cut site (logged in 1978) was covered with an incomplete canopy of bracken fern as well as a few immature conifers and decaying residual slash. In the summers of 1981, 1982, and 1985, both sites were instrumented; from September 1982 until September 1984 only the forest site was monitored. The principal findings are as follows: (1) for the forest site the daily mean α varies from 0.12 to 0.15 when the canopy is in full leaf in the summer; (2) in the winter the value of α goes to a minimum of 0.10 in the absence of snow, but immediately after a snowfall α can increase to about 0.50; (3) the value of α decays quickly after a snowfall and averages about 0.20 while snow remains on the ground beneath the canopy; (4) there is no clear relationship between α and the depth of snow on the forest floor; (5) there are well marked shoulders of change in α in the spring and autumn as the radiation balance of the forest adjusts to leaf-up and leaf-fall; (6) when the clear-cut site is fully vegetated in the summer α varies from 0.19 to 0.20 depending on the macroclimatic conditions, but when the bracken fern dies in the autumn α is reduced to 0.13, which is essentially the same as for the forest at this time; (7) an analysis of hourly data from the summers of 1982 and 1985 revealed that α depends on zenith angle for both sites, and these dependencies are strongly controlled by sky conditions and canopy wetness; they are strongest for clear skies and dry canopy states.

Résumé

L'exposé présente les résultats d'une étude à long terme (1981-1985) de l'albédo (α) d'une forêt ayant atteint le stade de la maturité et d'un terrain coupé à blanc, y compris les configurations diurnes et saisonnières.

Au cours des étés 1981, 1982 et 1985, on a installé des instruments dans une forêt constituée d'un peuplement mélangé de feuillus et de conifères et sur un site qui, après une coupe rase en 1978, était garni d'un couvert incomplet de fougères arborescentes et de quelques conifères immatures ainsi que de débris pourrissants de coupe. De septembre 1982 à septembre 1984, seule la forêt a fait l'objet d'une surveillance. Les principaux résultats obtenus sont les suivants: 1) dans la forêt, la moyenne quotidienne de α varie de 0,12 à 0,15 lorsque le feuillage du couvert a atteint sa pleine maturité en été; 2) en hiver, la valeur de α descend jusqu'à un minimum de 0,10 en l'absence de neige; toutefois, elle peut monter jusqu'à environ 0,50 immédiatement après une chute de neige; 3) la valeur de α diminue rapidement après une chute de neige et se stabilise aux environs de 0,20 en moyenne tant que la neige demeure au sol sous la voûte; 4) il n'existe pas de relation évidente entre α et l'épaisseur de la couche de neige sur le sol forestier; 5) les valeurs de α peuvent varier de façon marquée au printemps et à l'automne lorsque le bilan radiatif de la forêt s'adapte au développement du feuillage ainsi qu'à sa chute; 6) en été, lorsque la végétation du terrain coupé à blanc a atteint sa pleine maturité, α varie de 0,19 à 0,20 selon les conditions macroclimatiques; cependant, quand les fougères arborescentes meurent à l'automne, α est réduit à 0,13, soit essentiellement la valeur relevée dans la forêt à la même date; 7) une analyse des données horaires recueillies au cours des étés 1982 et 1985 a révélé que α dépend de l'angle zénithal aux deux emplacements et que cette dépendance est fortement déterminée par l'état du ciel ainsi que le degré d'humidité du couvert végétal; les valeurs de α sont les plus élevées lorsque le ciel est dégagé et que le feuillage du couvert est sec.

Introduction

There is a continuing interest in the characteristics of albedo, mainly because of its importance as a discriminator between surfaces in terms of their radiant behavior. Stewart (1971) described the variation of hourly albedo for Thetford Forest on the basis of 243 h of data. DeWalle and McGuire (1973) summarized hourly albedo for an oak forest in Pennsylvania for 16 d spread through the summer, autumn, and winter seasons. Moore (1976) documented the contrasts in albedo between a pine forest and an adjacent grassland site at Mt. Gambier, South Australia. Rouse (1984) and Rouse and Bello (1983) reported on the albedo of the stunted black spruce forest near the treeline at Churchill, Manitoba. Robinson and Kukla (1984, 1985) examined the change in albedo following a snowfall for a mixed forest and the impact of human activities on the regional albedo in southeastern New York. Recently, Pinker et al. (1980) and Shuttleworth et al. (1984) reported on the albedo of tropical forests in Thailand and Brazil, respectively; these studies represent a new direction in the literature.

The dataset presented here provides information on the short-term and long-term variation of α for a mixed forest stand and a clear-cut area between 1981 and 1985. The following will be discussed: (1) typical values and ranges in the daily albedo for both sites through all seasons, (2) the control exerted on the albedo by surface wetness and cloud cover, (3) the impact of snowfall on the forest's albedo and especially the change in its value immediately following a snowfall, and (4) the diurnal patterns of reflection on both sites in the summer under contrasting cloud and surface wetness.

Measurements

This study was conducted at the Petawawa National Forestry Institute (PNFI), Chalk River, Ontario (45°15′N, 77°25′W). In 1982 a survey, conducted in a 1050.7 m^2 sample area around the research tower, revealed an average density of 2664 stems ha^{-1} (McCaughey 1985). There were 1046 stems ha^{-1} for dbh > 5 cm (dbh = diameter at breast height) and 1618 stems ha^{-1} for dbh < 5 cm. In 1985, a more detailed sampling in a larger circular area (1963 m^2) showed a density of 1024 stems ha^{-1} for dbh > 5 cm which agrees to within 2% of the 1982 result. However, the density for dbh < 5 cm had increased dramatically to 5210 stems ha^{-1}. In the basal layer, 28% of the species were shrubs, 46% were coniferous seedlings, and 26% were hardwood seedlings. There is a distinct middle layer with a mean height of 9 m and a range from 3.5 to 16.0 m. In the upper layer the tree heights range from 14.0 to 22.0 m with a mean height of 20.0 m.

The clear-cut site was logged in 1978, and when measurements were started in 1981 it has been revegetated by a cover composed primarily of bracken fern. Before emergence of the fern in the spring, residual slash was evident on the site. During full canopy development in 1981 (the green season), the cover of fern was complete and the canopy was 1 m tall. At the end of August, the fern canopy died (the brown season). By 1985 bracken fern remained the dominant cover on this site, but there were numerous young conifers above the top of the canopy at the full vegetative stage in midsummer.

Global solar and reflected solar radiation were measured with Eppley pyranometers (model 8-48). In the summers of 1981, 1982, and 1985, both sites were instrumented; from September 1982 until September 1984, only the forest site was monitored. Global solar radiation was recorded at only the clear-cut site in 1981 and 1982, whereas in 1985, when both sites were used again, it was measured at each one. Hourly average values of radiation fluxes were used for the calculation of α, and the daily mean was found from the ratio of daytime totals. The daily mean albedo was judged to be the best variable to use to describe seasonal patterns of reflection from the sites.

In the 1981, 1982, and 1985 field seasons, rainfall was measured at the clear-cut site, and starting in September 1982 and continuing until September 1985, rainfall above the canopy at the forest site was measured. A tipping bucket gauge was used in each instance. The data from the forest were not used after the snow season started. Rather, in the winter, rainfall and snowfall values were used from the meteorological station located 3 km distant at the headquarters of PNFI.

Results

Seasonal Albedo: Forest and Clear-Cut Sites

The principal reason for the extensive data collection in this experiment was to describe the seasonal patterns of reflection over a whole year, especially for the forest surface, a canopy that exerts control on reflection in the winter. Unfortunately, for various logistical reasons there are no uninterrupted runs of data for a complete year. However, the seasonal picture can be built up using the available data from 5 yr.

The records for each year have been grouped into classes according to whether the canopy was (1) dry, or (2) wet, or (3) days with precipitation (rain or snow). Furthermore, the vegetative stage is important as a control on albedo. For the clear-cut site two distinct conditions, the green and brown season, exist. For the forest site, leaf-up in the spring and leaf-fall in the autumn are noticeable in the record of albedo. Finally, for the forest in the winter, the presence or absence of snow on or beneath the canopy is an important control of the albedo.

The summary statistics are presented in Table 1. Most of the 1981 data refer to the clear-cut site with only 5 d when values exist for the forest (Fig. 1). In the green season, up to day 240, the mean is steady at 0.20 for dry canopy conditions; there is less than a 1% decrease for wet canopy conditions. The value is abnormally low on day 227 because of overcast conditions and persistent rain. From day 241 α_c changes as a result of the senescence of the bracken fern, and the period mean is 0.13, the same as for the forest at this time.

In 1982 a longer run of data exists for both sites (Fig. 1). The clear-cut mean is steady at 0.19 with insignificant differences between wet and dry conditions (Table 1). The forest data extend well beyond those for the clear-cut and stop on day 329 just after the first snowfall. The decrease around day 278 (Oct. 5) is a result of leaf-fall. Before this, α_f averages 0.14, and afterwards a new stable value of 0.10 develops. As in the clear-cut site, there is no difference in α_f between wet and dry canopy states.

The 1983 forest results (Fig. 2) show the increase in α_f

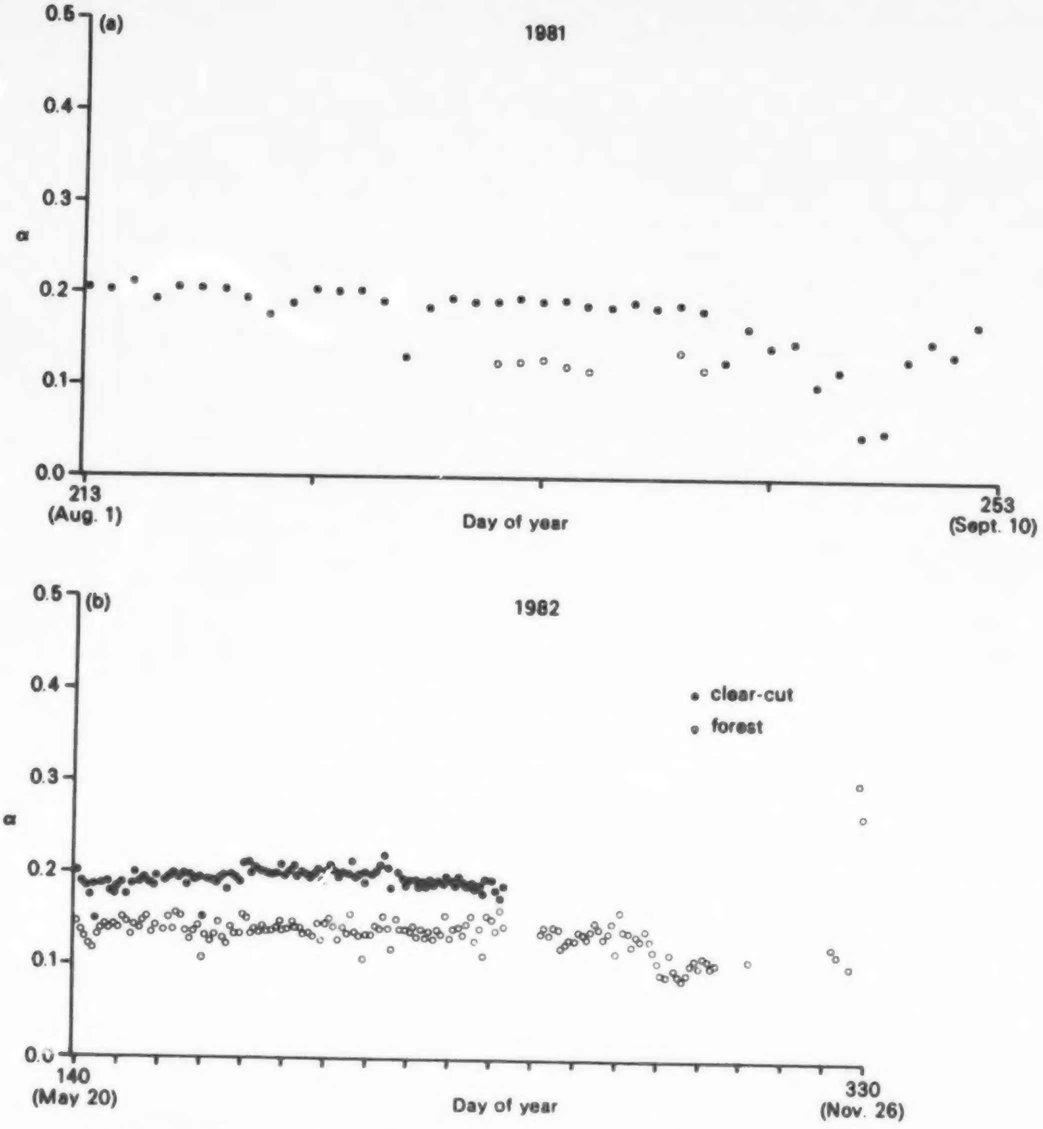

FIG. 1. Daily mean albedo for the forest and clear-cut sites in (a) 1981 and (b) 1982.

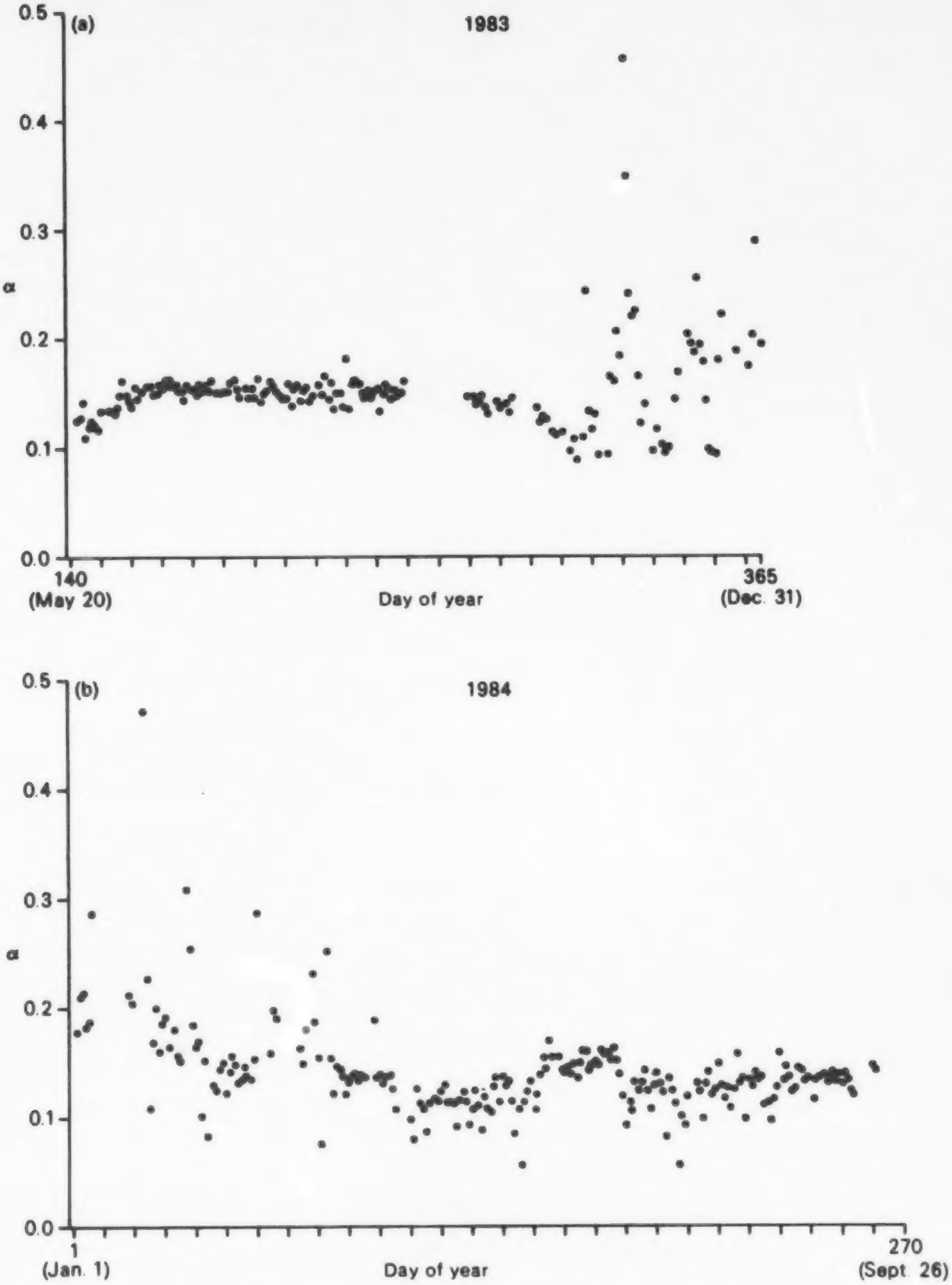

FIG. 2. Daily mean albedo for the forest site in (a) 1983 and (b) 1984.

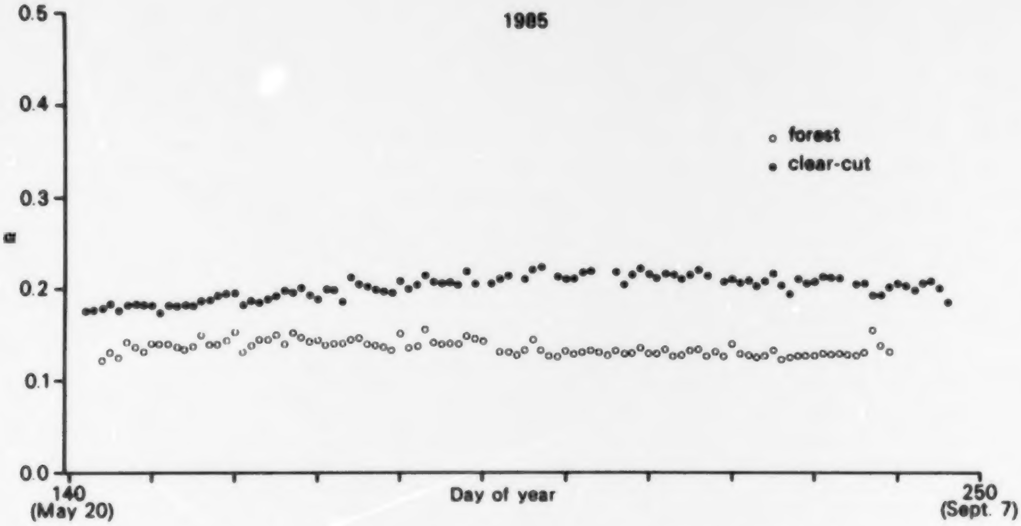

FIG. 3. Daily mean albedo for the forest and clear-cut sites in 1985.

TABLE 1. Summary of daily mean albedo values for forest (α_f) and clear-cut sites (α_c), Petawawa. (N = number of days in the group, SD = standard deviation, CV = coefficient of variation.)

Year	Site	Period (days)	Climatic conditions	N	Mean	SD	Min	Max	CV (%)
1981	forest	231-240	dry	5	0.130	.0063	0.124	0.140	4.82
			rain	2	0.121	.0021	0.119	0.122	1.76
	clear-cut	213-240 (green season)	dry	17	0.197	.0086	0.176	0.211	4.39
			rain	11	0.189	.0202	0.131	0.205	10.69
		241-252 (brown season)	dry + rain	12	0.128	.0394	0.052	0.173	30.91
1982	forest	140-278	dry	76	0.140	.0077	0.123	0.161	5.52
			rain	54	0.136	.0118	0.107	0.156	8.71
		280-329	dry	11	0.108	.0081	0.092	0.123	7.46
			rain	8	0.097	.0067	0.088	0.107	6.93
			snow	2	0.285	.0255	0.267	0.303	8.93
	clear-cut	139-243	dry	63	0.196	.0078	0.175	0.220	4.00
			rain	41	0.191	.0128	0.148	0.213	6.72
1983	forest	142-280	dry	74	0.151	.0093	0.121	0.183	6.12
			rain	40	0.142	.0173	0.091	0.164	12.25
		300-365	dry	21	0.163	.0721	0.090	0.350	44.19
			rain	8	0.162	.0462	0.100	0.227	28.44
			snow	15	0.188	.0886	0.095	0.458	47.04
			rain + snow	3	0.135	.0532	0.098	0.196	39.43
1984	forest	1-139	dry	62	0.144	.0408	0.079	0.308	28.32
			rain	23	0.124	.0422	0.075	0.286	33.92
			snow	18	0.220	.1050	0.107	0.509	47.70
			rain + snow	3	0.174	.0165	0.156	0.188	9.47
		140-261	dry	66	0.136	.0152	0.093	0.170	11.17
			rain	47	0.122	.0227	0.056	0.162	18.69
1985	forest	144-239	dry	54	0.134	.0079	0.122	0.154	5.94
			rain	41	0.135	.0082	0.122	0.152	6.11
	clear-cut	142-246	dry	56	0.200	.0133	0.176	0.223	6.65
			rain	42	0.201	.0108	0.174	0.218	5.38

as a result of leaf-up from day 140 to 160. From here until day 290 there is stability with a seasonal mean of 0.15, which is higher than in any of the other years. After the decrease in autumn, the winter data are characterized by marked variability, but there is a stable minimum of 0.10 which agrees with the 1982 results. The unstable pattern continues in 1984 (Fig. 2). The important controls on the albedo in the winter of 1983/84 are discussed in the following section. Whereas the mean of α_f in the summer of 1984 agrees with other years, it alone is characterized by the largest internal variability. The coefficients of variation of the group means for wet and dry canopy conditions (11% and 18%, respectively) are approximately double those for other years (Table 1).

In 1985, data are available for both sites, and very stable conditions are obvious (Fig. 3). For the clear-cut there is a very gradual increase from day 141 until day 180 representing the emergence and full development of the fern canopy. A similar trend was evident in 1982 but at that time was more rapid and lasted only 20 d. The forest values average 0.13 with no difference between wet and dry canopy states (Table 1).

WINTER 1983–84 ALBEDO: FOREST SITE

Winter recording was conducted at the forest site in 1982–83 and in 1983–84. The success of this effort was limited because, under the low temperature conditions encountered (minima of -30°C were common), it was difficult to get 100% data capture using cassette recorders.

The principal findings from the winter data analysis relate to the importance of snow as a control of the albedo (Fig. 4). The data start on October 28/83 and run to March 21/84 (day 145). Snow pulses, that is, the rise and fall of the albedo in response to a snowfall, are evident. Because of gaps in the radiation data, not all of these pulses are complete, but three are particularly obvious. First, on day 15 a 9-cm snowfall starts the albedo on an upward curve which is enhanced by two more snow events totaling 20 cm on days 19 and 20. The peak albedo is 0.46 which falls rapidly over the next 6 d to the starting value of 0.10. This fall is enhanced by the rain events between days 23 and 32. It is hypothesized that the rain melted the snow from the floor of the canopy as well as from the trees themselves. During

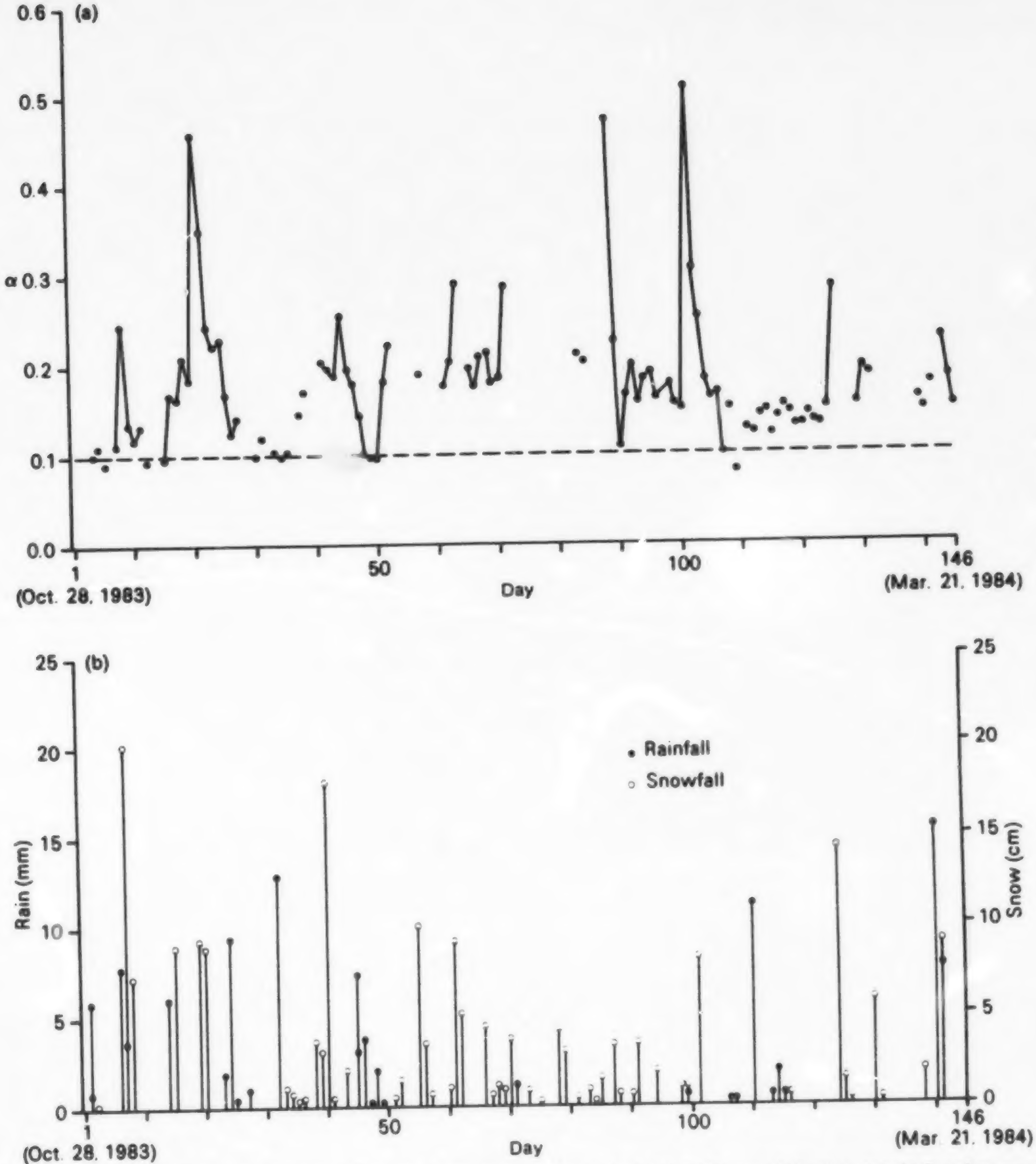

FIG. 4. a) Daily mean albedo for the forest site in the 1983/84 winter period. b) Daily precipitation totals for the same period.

the site visit on day 28 (Nov. 24/83) there were only scattered snow patches on the forest floor. Secondly, a very similar sequence is evident starting on day 101 when a snowfall of 8.2 cm spiked the albedo to a value of 0.51 which fell back over the next week to the minimum value. Again there were several rain events before the next significant snowfall on day 124. The third pulse, starting on day 89, is missing the rising part of the curve, but it has a maximum value of 0.47 which is very similar to the other two examples. The albedo falls rapidly over the next 2 d and stabilizes at a value of 0.18. The more rapid fall is interpreted as being the result of snow falling off the canopy but being preserved on the canopy floor. This conclusion is reinforced by the observation, during a site visit on day 90 (Jan. 24/84), that there was a 1-m-deep snowpack under the forest. The presence of the snowpack caused the albedo to increase to approximately double its winter minimum value of 0.10 under snow-free conditions. The higher minimum albedo of 0.18 is evident during the snow accumulation period from day 50 onwards.

The summary statistics for α during this period (Table 1) are given for four groups of days: dry, rain, snow, and snow + rain. No account was taken of time of precipitation and consequently, if it did not occur until evening, then an incorrect assignment of that day would be made from the point of view of its impact on surface reflection. As a result of the pulsing effect already discussed, the group means are not very instructive. More important are the ranges and

TABLE 2. Variation of albedo for forest (α_f) and clear-cut (α_c) sites for dry canopy conditions.

	Atmospheric transmissivity								
	< = 0.33			> = 0.34 to < 0.67			> = 0.67		
Zenith angle (°)	h	α_f	α_c	h	α_f	α_c	h	α_f	α_c
> = 85	5	.136	.136	14	.302	.248	15	.360	.320
> = 75 < 85	19	.123	.176	20	.224	.276	20	.270	.346
> = 65 < 75	20	.136	.184	20	.175	.225	20	.184	.231
> = 55 < 65	20	.134	.182	20	.150	.203	20	.142	.207
> = 45 < 55	20	.138	.189	20	.134	.198	20	.136	.196
> = 35 < 45	24	.143	.184	20	.132	.190	20	.130	.189
> = 26 < 35	24	.134	.179	24	.133	.190	28	.124	.182
< 26	10	.134	.187	16	.134	.186	12	.123	.181

coefficients of variation. The latter, except the rain + snow group, are higher (>28%) than for any of the other summer periods. Clearly, for winter conditions it is important to interpret the dynamic behavior of α, that is, taking into account the very rapid changes imposed by the presence or absence of snow. Immediately following a snowfall that is heavy enough to coat the canopy, α increases to around 0.50. As the snow falls from the canopy, α decreases rapidly to a minimum value of either 0.10 if no snow remains on the forest floor or a value around 0.20 if a snowpack exists beneath the canopy. The presence of rain events hastens the return of the albedo to either of the two minima.

HOURLY ALBEDO: FOREST AND CLEAR-CUT SITES

An analysis of the variation of the hourly average albedo for the two sites was performed on a sample of 30 d selected from 1982 when the surfaces were dry. These were subdivided into groups of 10 on the basis of daily atmospheric transmissivity, calculated as the ratio of the daily totals of global solar radiation and extraterrestrial radiation, which is used as an index of cloudiness. Over the summer, the transmissivity varied from a minimum of 0.06 to a maximum of 0.71, and from field observations the transmissivity for clear, cloudless days tended towards 0.70, while for overcast conditions it was <0.30. For partly cloudy conditions it ranged widely from 0.30 to 0.60, as a result of the occurrence of different cloud types. Stewart (1971) used transmissivity as an index of sky condition in a study of the albedo of Thetford Forest; his transmissivity classes were <0.33, 0.33 to 0.67, and >0.67 which represented overcast, partly cloudy, and clear conditions. The Petawawa findings agree closely with these limits and therefore, the same transmissivity classes were used to group the sample days. Finally, another group of 6 d was chosen to characterize the behavior of α for wet canopy conditions on the basis of the precipitation record. If significant rain fell on the previous day or before sunrise of the sample day, then it was placed in the wet canopy category. In this group only the overcast and partly cloudy transmissivity classes are represented.

For each group, the behavior of α as a function of zenith angle was examined, and the results for dry canopy conditions are presented in Table 2 where the group mean in each zenith angle class is used to characterize the distribution.

TABLE 3. Comparison of albedo for clear-cut site in 1982 and 1985 when atmospheric transmissivity > = 0.34.

Zenith angle (°)	N	1982	N	1985
> = 85	29	.284	23	.297
> = 75 < 85	40	.311	24	.291
> = 65 < 75	40	.228	24	.243
> = 55 < 65	40	.205	24	.210
> = 45 < 55	40	.197	24	.195
> = 35 < 45	40	.190	24	.184
> = 26 < 35	52	.186	26	.179
< 26	28	.183	22	.180

TABLE 4. Comparison of albedo for wet and dry canopy conditions for forest (α_f) and clear-cut (α_c) sites.

A. Atmospheric transmissivity < = 0.33

Zenith angle (°)	Wet canopy			Dry canopy		
	h	α_f	α_c	h	α_f	α_c
> = 85	1	.330	.280	5	.136	.136
> = 75 < 85	5	.176	.204	19	.123	.176
> = 65 < 75	6	.163	.213	20	.136	.184
> = 55 < 65	6	.142	.195	20	.134	.182
> = 45 < 55	6	.150	.187	20	.138	.189
> = 35 < 45	8	.128	.186	24	.143	.184
> = 26 < 35	8	.121	.181	24	.134	.179
< 26	0	-	-	10	.134	.187

B. Atmospheric transmissivity > = 0.34 < 0.67

Zenith angle (°)	Wet canopy			Dry canopy		
	h	α_f	α_c	h	α_f	α_c
> = 85	3	.187	.253	14	.302	.248
> = 75 < 85	8	.186	.234	20	.224	.276
> = 65 < 75	8	.153	.201	20	.175	.225
> = 55 < 65	8	.136	.193	20	.150	.203
> = 45 < 55	8	.133	.190	20	.134	.198
> = 35 < 45	8	.119	.186	20	.132	.190
> = 26 < 35	8	.120	.185	24	.133	.190
< 26	8	.129	.185	16	.134	.186

For overcast conditions there is no discernible dependence of α on zenith angle for either the forest or clear-cut sites. For partly cloudy and clear conditions the dependence is strong for both sites.

The reduction of α_c for the highest zenith angle class in each of the transmissivity groups was unexpected. This could be a result of horizon interference at high zenith angle or the view factor of the inverted pyranometer may have been unique. To investigate this issue further, a comparison was made of the albedos for this site in 1982 and 1985 (Table 3). In 1985, the pyranometers were at a height of 6 m in a different part of the site than in 1982 when the instruments were at a height of 2 m. For zenith angles <65° the difference in α is <1%, and the maximum difference is only 2%. In 1985, for zenith angles >80°, there is no obvious depression of α but rather a plateau in a rising curve. On the basis of this evidence it is concluded that the albedo for the bracken fern does not depend strongly on zenith angle above 80° when the canopy is dry.

The differences in albedo between wet and dry canopy states are summarized in Table 4. For overcast conditions for both sites the presence of water has minimal effect for low zenith angles. Above a zenith angle of 60° the wet surfaces reflect more, and in the case of the clear-cut site there is no evidence of a depression or plateau in the albedo distribution above 80°. Under partly cloudy conditions both sites behave in the same fashion as for overcast conditions with minimal differences for low zenith angles. There are significant differences for zenith angles above 60° with the wet surface always reflecting less. However, for the clear-cut site, when the zenith angle is >85° there is no difference because of the depression in the dry-surface curve which is absent when the surface is wet.

Acknowledgments

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TRIM Development Update: CORE and TRIMIN for Dendroclimatological Radial Sequences

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Abstract

A new hardware/software product has been developed that expands the application of the Tree Ring Increment Measuring (TRIM) System.

CORE (COre REader), as the name implies, is intended for the measurement of tree increment cores. CORE is designed to securely hold the increment core under pressure (off-set cam) throughout the complete core length, with the core section protruding slightly above the surrounding flat preparation surface. CORE is water-resistant with a flourescent tube backlight and interchangeable colored filters to highlight the ring boundaries for different tree species.

TRIMIN is a new data input software package that error-checks, stores, prints, and plots the radial sequences for dendroclimatological analysis.

Résumé

On a conçu un nouveau matériel/logiciel qui permet d'étendre l'application du Système de mesure des cernes de croissance dans les arbres (TRIM).

CORE (COre REader), comme son nom l'indique, est utilisé pour la mesure de carottes où apparaissent des cernes d'arbres. CORE a été élaboré de façon à maintenir solidement la carotte sous pression (came déportée) sur toute sa longueur, la section de carotte émergeant légèrement au-dessus de la surface plane de préparation environnante. CORE, qui résiste à l'eau, comporte un tube fluorescent produisant un contre-jour ainsi que des filtres colorés interchangeables afin de faire ressortir les limites des cernes pour différentes espèces d'arbres.

TRIMIN est un nouveau logiciel d'entrée des données, qui repère les erreurs, mémorise, imprime et trace les séquences radiales en vue de l'analyse dendroclimatologique.

Introduction

A stand-alone, microcomputer Tree Ring Increment Measuring (TRIM) System was developed for precise measurements of tree ring widths and growth layer analysis (Fayle and MacIver 1986).

The patterns of successive changes in width and length of the annual growth layer integrate much of its history. The detection of changes in ring width and their subsequent biological interpretation depends on both the radial sequences for the individual trees and trees aggregated on a unit area basis. Whole tree destructive sampling at sufficiently close intervals is required to document the radial and longitudinal patterns of growth. CORE (COre REader) was developed for circumstances where unit area sampling per stand with detailed whole tree growth layer analysis is not possible.

Discussion

CORE, as the name implies, is intended for the measurement of tree increment cores. The increment core is securely held in place throughout the complete core length by an off-set cam mechanism with the core section protruding slightly above the surrounding flat preparation surface (Fig. 1). CORE is water-resistant with a flourescent backlight and interchangeable colored filters to highlight the ring boundaries for different tree species.

CORE mounts directly on the measuring platform of the TRIM table and is held securely in place by adjustable thumb screws. These predrilled holes are currently available on all new TRIM models with registration numbers exceeding 8507. Older TRIM Systems will require the removeable platform to be precisely drilled and tapped.

TRIMIN is a new software package for tree section or

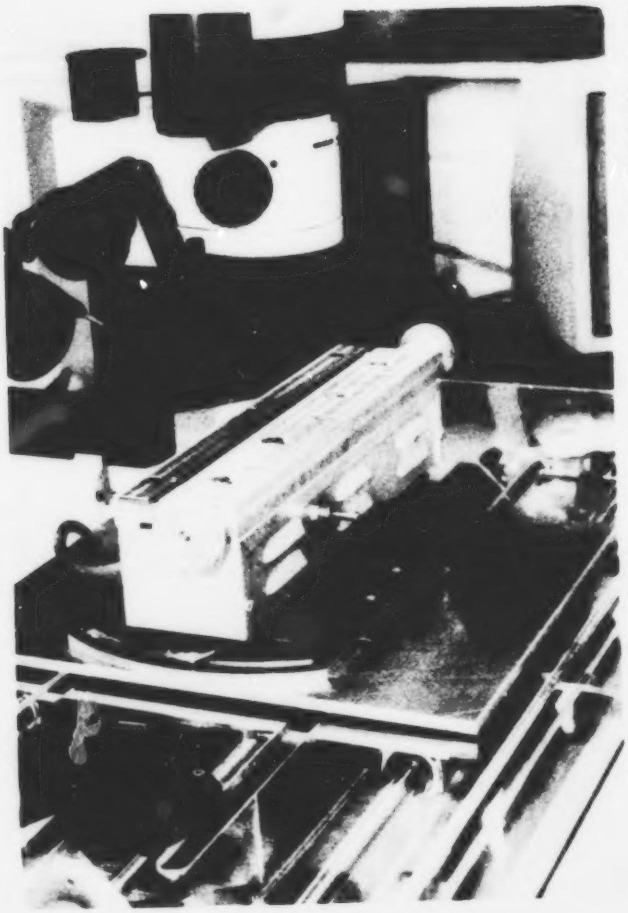

FIG. 1. CORE (COre REader) measures tree increment cores.

increment core data input with graphical output. TRIMIN has three principal modules — tree measurement, core measurement, and data recall. In the first two modules, TRIMIN has the ability to extensively error-check the incoming data, store data for later growth layer analysis, with double high resolution printing and plot radial sequence graphs. Recalling for graphical overlaying of current or previously recorded radial sequences (tree and/or core sections) is particularly relevant for dendroclimatological applications.

TRIMIN is designed to operate on a 128K enhanced Apple IIe dual drive system with a 132 column Epson printer and a Hewlitt/Packard six-pen plotter. Both TRIMIN and CORE are completely compatible with existing TRIM hardware specifications.

Relationships have been investigated between whole tree cambial responses as defined by the specific volume increment (SVI) and increment core sequences for ring width taken at breast height. For example, "prime" growth jack pine stands by unit area were identified by coring (two cardinal cores at 130 cm high) and calibrated with individual whole trees selected for complete growth layer analysis. "Prime" growth chronologies were defined when the ring widths taken at breast height (130 cm) exceeded 5 mm within 3-5 yr from the pith.

Figure 1 is a simple illustration where the integrated analysis between whole tree and increment core chronologies provides a field assessment index for site productivity. Calibration and adjustment of tree increment cores depends on whole tree destructive sampling and identification of characteristic dendroclimatological patterns. For example, specific extreme climatological events serve as excellent growth reference indicators for precise calibration of the radial sequences. Engineering diagrams, software, and detailed instruction manuals are available on request.

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Night Temperature Control of Bud Initiation

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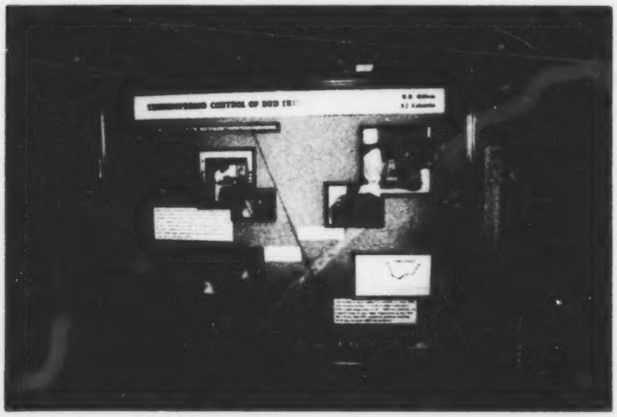

The time required for black spruce (*Picea mariana* (Mill.) B.S.P.) container seedlings to initiate buds and to subsequently reach acceptable levels of frost hardiness is profoundly affected by greenhouse night temperatures. In plant growth chamber experiments daylengths were shortened to simulate the naturally declining daylengths that occur in the fall at an average latitude for growers in Northern Ontario (48°N, beginning September 1). Day temperature was maintained at 26°C while night temperatures were set at 5, 7.5, 10, 14, 18, 22, 24, or 26°C. Twice weekly, seedlings were destructively sampled from each treatment and examined under a dissecting microscope for bud initiation, indicated by the presence of newly differentiated budscales. The time required for black spruce seedlings to reach 100% bud initiation varied dramatically, depending on night temperature (Fig. 1). Bud initiation was fastest when night temperatures were between 10° and 24°C, the optimum temperature being 14°C. Night temperatures less than 10°C or above 26°C dramatically increased the time required for seedlings to attain 100% bud initiation.

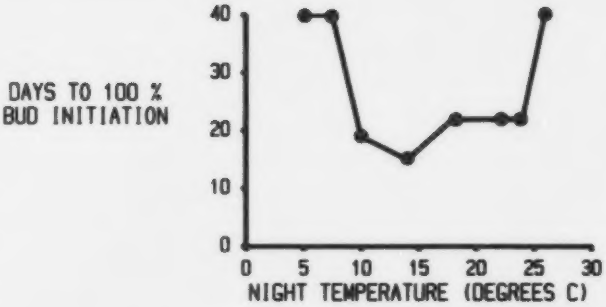

FIG. 1.

The effect of night temperatures on the rate of bud initiation in black spruce seedlings.

Bud, Cone, and Shoot Development of White Spruce (*Picea glauca* (Moench) Voss) Within Crown Patterns and Microclimate

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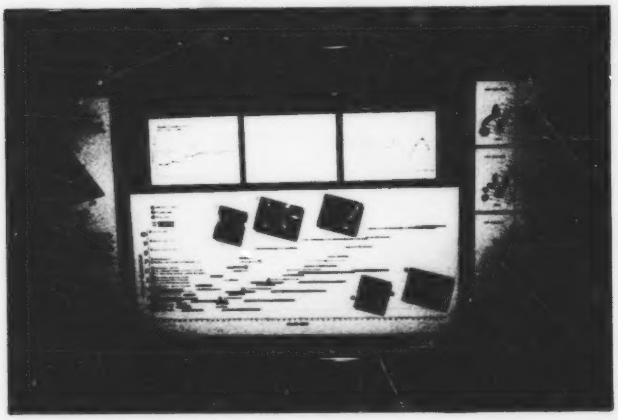

The development of buds, cones, and shoots from selected branches at comparable positions within the crowns of 70 white spruce (*Picea glauca* (Moench) Voss) ramets (10 clones, 7 ramets/clone) was observed in years 11 and 12 after establishment of the trees in a clonal seed orchard at Glencairn, Ontario. Sequential patterns of change in development of the different structures were observed and the manners in which phenological changes proceeded within the crown were identified. Variation in onset and duration of developmental stages between north and south crown aspects, among branches, within clones and among clones was determined.

Postdormancy development of seed cones and pollen cones was generally more advanced at distal shoot positions than at proximal positions (some exceptions occurred among pollen cones). Within separate identifiable zones of seed cone and pollen cone initiation, among-branch development of cones was more advanced in upper than in lower branch-whorl positions. Vegetative-bud development was generally more advanced at proximal than at distal shoot positions. Among branches, development of vegetative buds was more advanced in lower than in upper whorl positions. The onset of stages of vegetative and reproductive development was generally more advanced on the south-facing than on the north-facing crown portion. Timing of reproductive and vegetative development was earlier in 1985 than in 1984, and differences were greatest for seed cones. The relative overlap of pollen-cone and seed-cone development was greater in 1984 than in 1985 but amounts varied for different clones.

Chromel/constantan thermocouples were inserted into the bases of selected vegetative and reproductive buds in late April of 1985. Temperature responses were processed and stored in a CR7 datalogging system with hourly mean, maximum, and minimum values recorded over each 24-h period for the duration of the study. A climatological station was established in the orchard in 1984. Instruments monitored temperature and solar radiation at levels above and among the ramet crowns; relative humidity, net radiation, wind speed, and direction above the ramet crowns; soil temperature at 10 cm below the soil surface, and precipitation on level ground. Hourly mean, maximum, and minimum values were recorded for each 24-h period, from early April to early July in 1984 and 1985, and stored in a CR21 datalogging system.

Temperature patterns within and among branches, between crown aspects, among four time periods (0100–0600, 0700–1200, 1300–1800, 1900–2400), among seasonal periods, and among years were observed. Potential influences of temperature and of other monitored climatic factors on observed vegetative and reproductive development were identified. Association of climatic events with bud, cone, and shoot phenology were subsequently investigated.

Promises of Anemothermographic Remote Sensing for Surveying Forest Microclimates in Recent Loggings

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Wood logging in clear cuts or strip cuts creates a drastic change of the microclimate which will affect artificial reforestation or natural regeneration. For instance, a seedling of black spruce (*Picea mariana* (Mill.) B.S.P.) will often vegetate for 30 yr before reaching normal growth rates (Fayle and MacIver 1986). Similar observations by the above authors in the strip cuts already studied by Frisque and Vézina (1977) have shown that this type of plant hardly reaches a height of 50 cm after 15 yr in Northern Quebec. Due to the intense nocturnal radiative cooling in anticyclonic weather, the terrain hollows become cold air accumulation sites through katabatic along down the neighboring slopes.

Consequently, newly open buds in those areas are massively destroyed by the late springtime nocturnal frost, while the surviving ones suffer from a significantly reduced growth season, in terms of degree-days above 5°C. On higher terrain, new plants are affected by daytime wind drying action, as well as by an often excessive drainage of the water table.

A preliminary study of microclimates in a sample of clear and strip cuts on flat and hilly sites has been conducted through the use of anemothermographic remote sensing in the boreal forest of Northern Quebec(Verreault et al.1985; Lemieux et al. 1988). The anemothermographic remote sensing combines airborne measurements of both the radiative temperature of different objects on the ground (water surfaces, bare soil, litter, tree canopy, etc.) and the cold air circulation near the ground (katabatic air drainage, land breeze, etc.). This results in a detailed mapping of those micrometeorological parameters over areas ranging from a few hundred to a few thousand hectares. In our recent case studies, the thermographic and anemographic flights have been made as distinct operations and the results combined afterwards at the analysis stage. However, the forthcoming development of the method will deal with simultaneous measurements of temperature and wind velocity in a single flight.

The thermographic images used so far were analogical reconstructions obtained through numerical processing of the data from a DAEDALUS scanning radiometer (CCT) in the spectral band of 8–14 μm. Typical nocturnal temperature differences ranging from 5 to 10°C are observed between strip cuts and the adjacent standing forest canopies, as well as between the lower and higher parts of clear cuts. Such thermographic pictures enable one to pinpoint the localization of frost pockets and to view the radiation screening effect of the standing trees in the lateral parts of strip cuts.

The anemographic remote sensing, in its earlier version, made use of the simultaneous nocturnal aerial photography of several especially designed wind transducers which were previously installed at 1 m above the ground and disposed in a bidimensional network over a large area (typically 1 km^2). These mechano-optical devices, which were described elsewhere (Verreault et al.1985), could be detected at night from as high as 2500 m merely with an array of 32 ordinary photographic flashtubes fixed underneath the plane. The subsequent interpretation of those photographs gives both wind speed and direction for each network site, thus yielding the circulation pattern of cold air at 1 m above the ground.

It becomes sometimes prohibitive for a ground crew to pre-install a wind transducer network in northern forest areas that are inaccessible. Therefore, the present development in airborne anemography considers replacing the above transducers by smoke plumes, the geometry of which can be related to both wind speed and direction. Particularly, in the very stable nocturnal air layer near the ground with anticyclonic, frostprone weather, the plume from a commercial smoke grenade remains within a few metres from the surface and thus provides a good indication of low-level cold air circulation patterns. In this manner, remote, sparsely settled areas can now be studied by first launching smoke grenades from the plane onto the site of interest, then by flying back over the area for optical data acquisition.

The latest improvement of the method consists of superimposing over a conventional thermographic image of terrain, the image of the warm plume from either a smoke canister or an infrared-absorbing tracer-gas generator by means of a thermal-infrared scanning detector such as the AGEMA 870 thermovision camera. This yields at the same time a simultaneous anemothermographic video image in real time and a videotape suitable for subsequent numerical image processing.

The study of forest microclimates by anemothermographic remote sensing appears to be promising not only in locating frost pockets, but also in determining cold air circulation patterns. It is then possible to exploit the natural cold air dynamics for draining, for instance, cold air retention areas toward warm, low lying water surfaces through appropriate breaches cut in the forest belt around the lakes.

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Climatograms by Soil Type for Ontario

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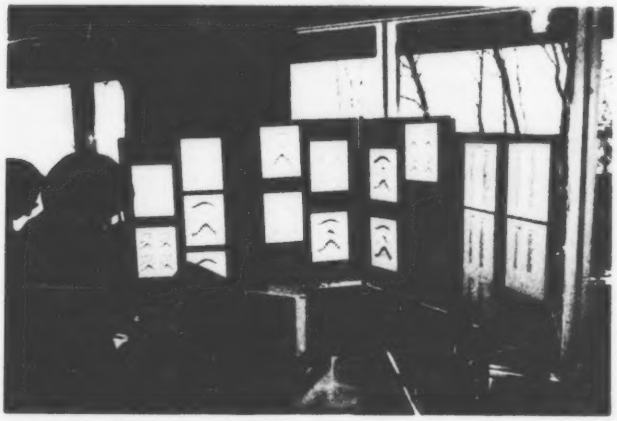

Abstract

Climate and it's variability over time and space directly influence wood production. To better understand this macroclimatic variability and in support of TRIM growth models, standardized microcomputer-generated climatograms by soil type have been assembled for long-term (1951–80) climate stations in Ontario.

Résumé

Le climat et sa variabilité en fonction du temps et de l'espace ont un effet direct sur la production du bois. Afin de mieux comprendre cette variabilité macroclimatique et de compléter les modèles de croissance TRIM, on a élaboré, par type de sol, des climogrammes normalisés, produits par micro-ordinateurs, pour des stations climatiques à long terme (1951-1980) en Ontario.

Introduction

Climate and it's variability over time and space directly influence wood production. Geographically, some areas of Ontario are ideally balanced with appropriate climatic interaction for optimal forest growth and production, whereas other areas are subject to climatic stress conditions of varying intensities.

To better understand this macroclimatic variability and in support of the TRIM growth models (MacIver 1988) standardized microcomputer-generated climatograms have been assembled, analyzed, and documented for more than 100 long-term climatic stations in Ontario. The climatic data for the period 1951–80 was extracted from published sources, the computer archives of Environment Canada, and/or numerically calculated and plotted on the climatograms.

Discussion

There are four climatograms plotted per page (Figs 1–4), one for each of four characteristic soil types: clay, clay–silt loam, sand loam, and sand. Only the water balance calculations change on each climatogram in response to the water-holding capacity of each characteristic soil type.

Each climatogram is standardized and consistent in the plotting location of each climatic parameter with five main modules. An interpretation key is provided in Figure 5. If the data does not exist or if the user wishes to introduce field observations for soil moisture, then slight modifications to the computer program allows for this flexibility and plotting. At present the modules are partitioned into:

1) locational and elevational parameters,
2) annual and seasonal values plus monthly temperature trends,
3) water balance including precipitation profiles,
4) monthly growing degree-day frequencies above the bases of 0°C and 5°C,
5) monthly frequencies of rain and snow days.

The water-holding capacity of any soil depends on several factors including composition, structure, and depth. For this exercise, the water-holding capacities are based on soil texture as defined by Agriculture Canada (Kirkwood et al. 1983). At any specific microsite location these characteristic water-holding capacity thresholds may be of concern. If this is the case, the water balance software module was developed to accommodate alternate threshold value to meet the user's definitions and needs.

The current water balance approach, based on Thornthwaite (1948) and enhanced by Johnston and Louie (1983), assumes that in the initial growing stage, water withdrawal is unrestricted in response to the atmospheric demand. However, beyond a point, moisture withdrawal is subject to a resistance factor. For the four characteristic soil types, the maximum water-holding capacities range from 280 mm for clay, 200 clay–silt loam, 150 for sand loam, to 100 for sand soils.

In the calculation and development of these water balance software programs, the water balance used the 30-yr thermal and moisture averages as input to ensure the monthly continuance of the water deficit and surplus calculations. In this way, the final soil moisture retentions of, for example, June, represent the initial moisture levels for July. This approach differs from the previous techniques (MacIver and Masterton 1984) and the user is advised to verify the technology before application.

The software programs are menu-driven, interactive, and developed for an enhanced Apple IIe microcomputer with dual disk drives and a Hewlett-Packard 6 pen plotter.

This standard climatogram/soil type technology package has been transferred to the Atmospheric Environment Service, Environment Canada; Ontario Ministry of Agriculture and Food; Alberta Forest Research Centre; plus numerous regions within the Ontario Ministry of Natural Resources. The computer software program and instruction manual are available on request.

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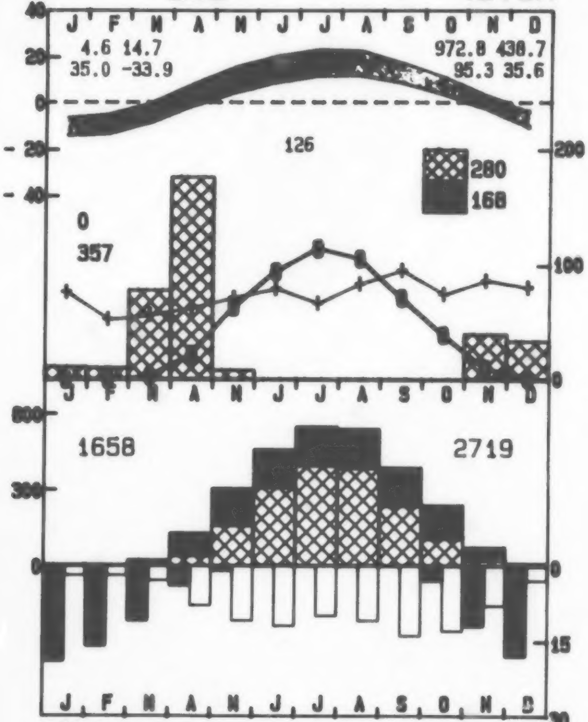


Figure 1

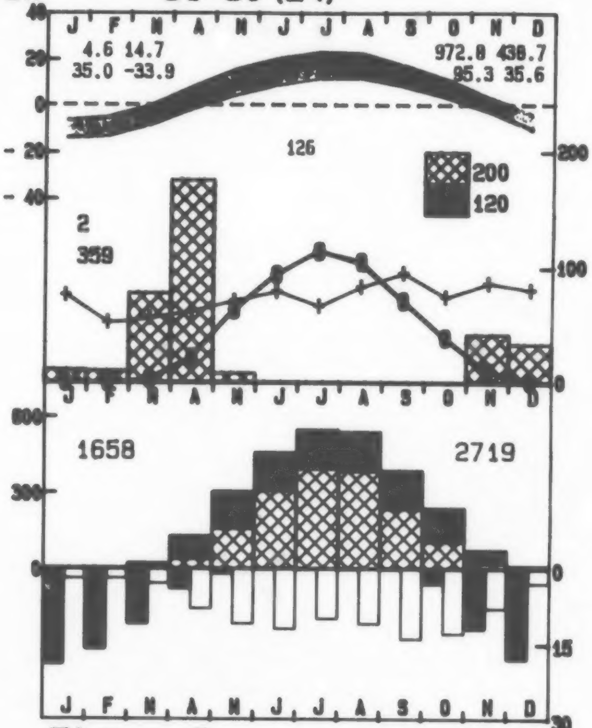
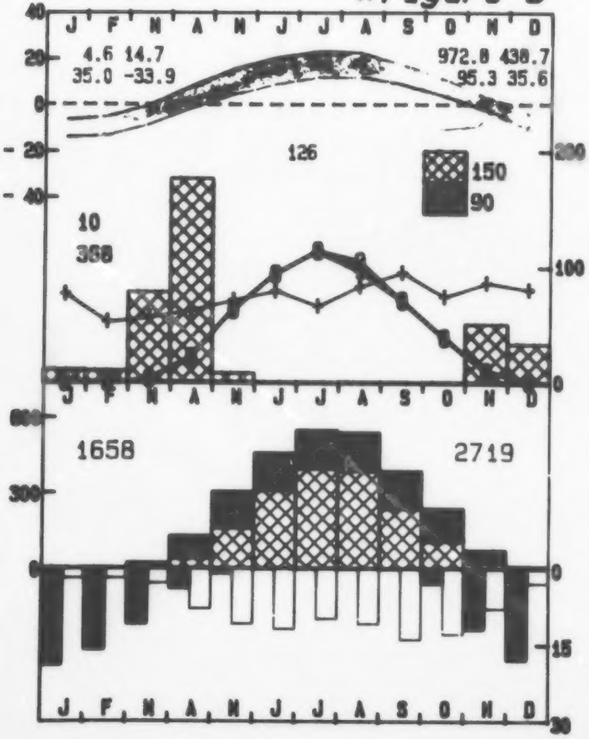


Figure 2

**Figure 3*



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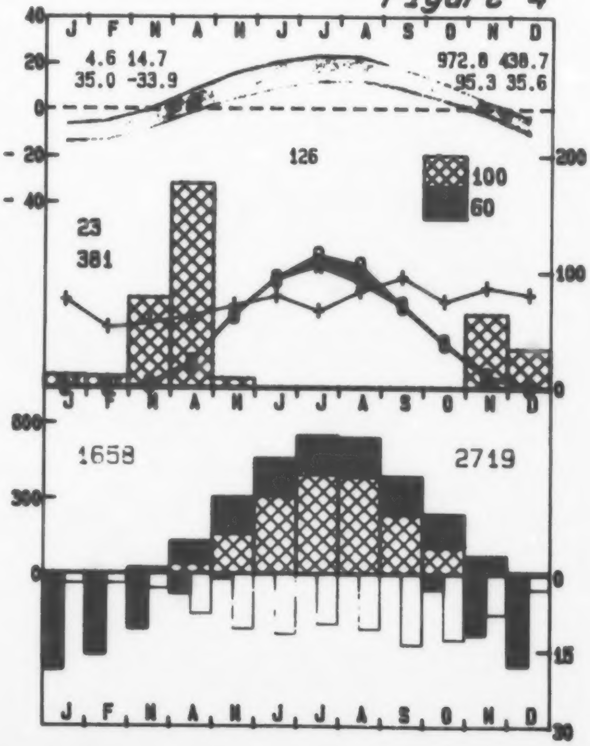

Figs 1–4.

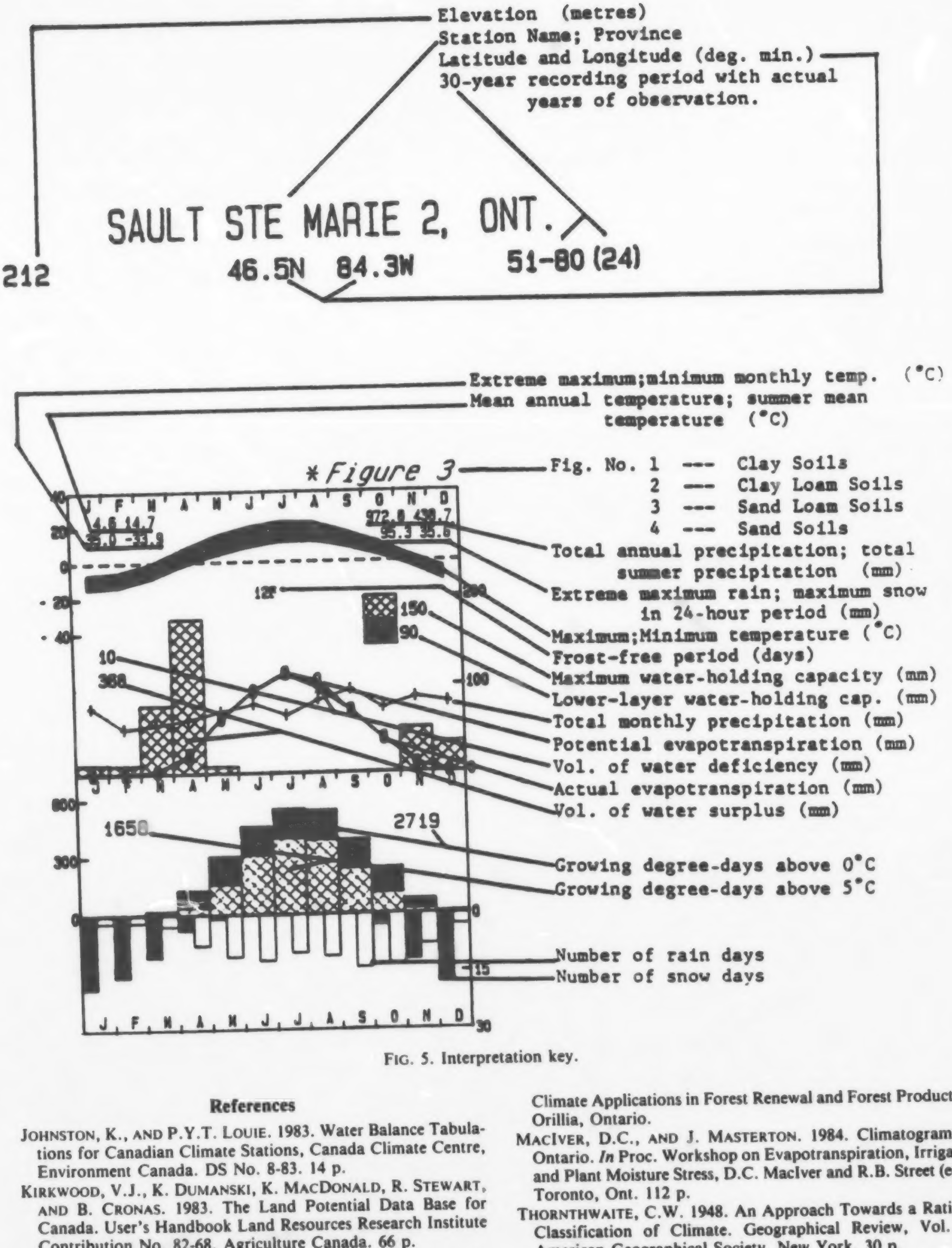

FIG. 5. Interpretation key.

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Provisional Climate-Productivity Map for Jack Pine in Ontario

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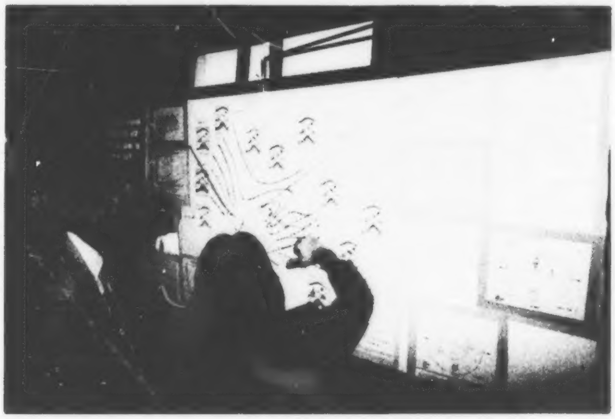

Abstract

A provisional climate-productivity map is presented based on biological thresholds derived from the reconstructed growth and development patterns of jack pine (*Pinus banksiana* Lamb.) stands in Ontario. Productivity regions are defined for jack pine by growing season temperature and precipitation parameters with further discrimination provided by atmospheric thermal stress and volume of water deficiencies by soil types.

Verification of the relative homogeneity of productivity regions are provided by replicated plots per stand in terms of: (1) growth and development curves for mean volume over age by forest stand; (2) spatial mapping of the species-spacing (stand structure) interactions by plot unit area and soil textural stratification.

Iterative refinement of this provisional map for jack pine will continue with TRIM additions from specific field locations throughout Ontario.

Résumé

Cet exposé présente une carte provisoire de climat-productivité basée sur des seuils biologiques dérivés de modèles reconstruits de croissance et de développement des peuplements de pins gris (*Pinus banksiana* Lamb.) en Ontario. Des zones de productivité sont définies pour le pin gris selon des paramètres de température et de précipitations pour la saison de croissance, une distinction additionnelle étant obtenue au moyen de données sur le stress atmosphérique et l'insuffisance d'eau en volume par type de sol.

On vérifie l'homogénéité relative des zones de productivité dans des placettes, par répétition et par peuplement en ce qui concerne: 1. les courbes de croissance et de développement pour le volume moyen en fonction de l'âge par peuplement forestier, et 2. la cartographie spatiale des interactions espèces - espacement (structure du peuplement) par unité de superficie de placette et stratification texturale du sol.

On continuera de perfectionner de façon itérative cette carte provisoire dressée pour le pin gris à l'aide de données TRIM relevées à des emplacements déterminés sur tout le territoire de l'Ontario.

Introduction

The synoptic environment directly affects forest productivity, with productivity defined as volume by unit area over time. Scarce forestry data sets with the required analytical precision and biological sensitivity currently exist within the new forest (0–20 age). Extensive reconstruction sampling methodologies by unit area and growth layer analysis models were developed based on annual ring width data captured by the computerized Tree Ring Increment Measuring (TRIM) System (Fayle and MacIver 1986).

Management prescribes treatments most easily where and when catastrophic or extreme climate events cause incremental stand slowdowns, declines, or mortality. However, within the new forest, prescriptions must be preventative to balance several interrelated stress factors of which climate is most definitely a major contributor. Likewise, species-spacing (stand structure) and limiting soil factors also play major contributing roles with additive and periodic stress provided by such agents as air pollution and insects. To better understand the cumulative influence of the above causative factors on forest growth and development, an integrated productivity model with temporal and spatial mapping for jack pine in Ontario was developed.

Discussion

To accomplish this first approximation model required the assembling and re-analysis of current and historical complete tree data bases from randomly replicated destructively sampled plots per jack pine stand. In all cases, the destructively sampled individual trees were analyzed in accordance with the TRIM growth layer analytical procedures, then aggregated to the plot-stand-regional levels of volume performance. Further stratification of this data base also depended on the associated physical soil descriptions and unit area mapping of all species (stand structure). In this latter case, a species-spacing algorithm was applied

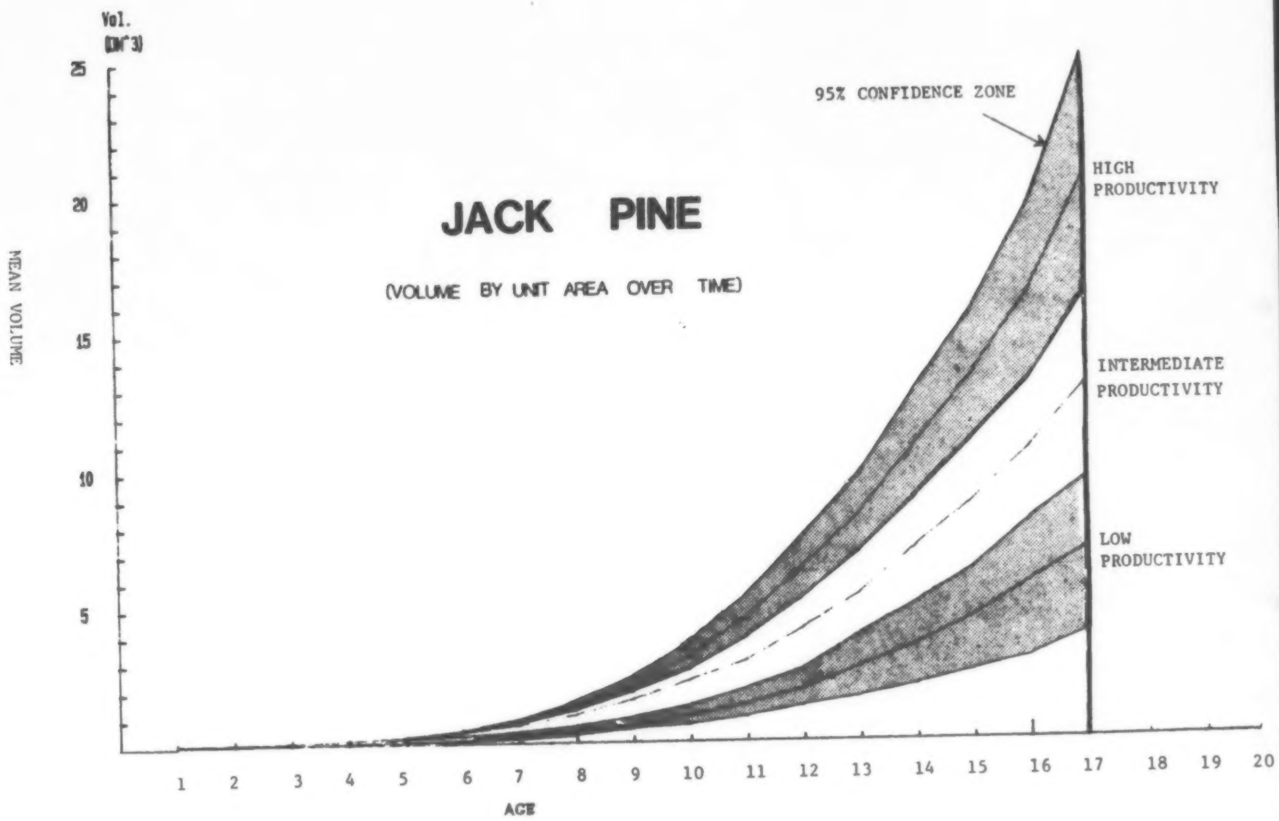

FIG. 1. High, intermediate, and low productivity curves with their respective 95% confidence limits as defined by volume over age for jack pine (*Pinus banksiana* Lamb.) stands.

to separate the spatial distribution of the stand into one of three basic forms — clustered, random, or uniform. Climatograms by soil type for Ontario (MacIver 1988b) were developed separately to support this temporal and spatial productivity analysis.

The dynamic initial growth characteristics of jack pine, especially the natural cohorts, result in a narrow establishment window. For example, silviculture surveys that concentrate on the survival frequency of planted and natural jack pine within the first 10 yr can provide a sound operational basis for plot/stand/forest aging.

Statistically separate volume production curves were developed for this new jack pine forest estate (0–17 age). As noted in Figure 1, the 95% confidence intervals are plotted about the mean volume by unit area over age relationships to identify high, intermediate, and low productivity levels.

Against these base reference curves, other soil types, stand structure patterns, and climatic regions can be superimposed to evaluate, within an economic framework, their relative and anticipated production schedules. As a diagnostic reference, the forest manager can detect deviations from this expected level of performance; identify the possible cause; and prescribe the appropriate remedial action. For example, effective thinning for high productivity jack pine stands should occur before age 13. Delays result in stand stagnation with significant volume slowdowns by age 20.

The mapping of these productivity levels for jack pine in Ontario is a further planning aid for the forest manager (MacIver 1988a). For example, the distinctive "wave" pattern of productivity levels across Northern Ontario reflects the dominant influence of the synoptic environment modified by the Great Lakes, especially Lake Superior. Silviculture practices and their operational scheduling would directly benefit from greater integration of synoptic weather forecasts and climatic monitoring programs.

Iterative refinement of this first-approximation mapping is strongly suggested based on additional climatic data coupled with TRIM growth layer analysis from specific geographical locations throughout Ontario.

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A Parameter Specifically Designed for Conifer Seedlings

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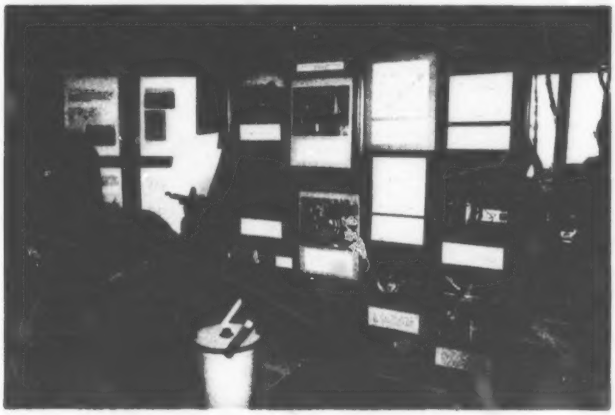

A transient-type ventilated diffusion parameter, originally reported by Livingston et al. (1984), but now significantly modified and improved, has been developed to enable repeated nondestructive measurements of average stomatal conductance of whole conifer seedlings. The unit relies on a fast-response Vaisala Inc. Humicap (capacitive thin-film type) relative humidity (RH) sensor to measure changes in RH inside a stainless-steel chamber placed over a seedling growing in the forest or nursery. Increase in RH due to seedling transpiration is used to determine the flux of water vapor into the chamber and hence the rate of transpiration and average stomatal conductance. Measurements of temperature and RH, and all subsequent calculations, are controlled using CMOS circuitry with an RCA 1806 microprocessor.

Temperature measurements required to calculate the saturation vapor density inside the chamber are made using a Fenwal UUT 51J1 (100 kilohm) bead thermistor (minimizing self-heating errors associated with the 3 kilohm thermistor used in earlier prototypes). The thermistor oscillator circuit is disabled when the RH sensor is activated, which eliminates noise in the measurement due to oscillator interference. The internal software has been extensively rewritten to analyze the parameter's output more easily, and to increase the precision of the arithmetic routines. The chamber design has been modified to make installation over a seedling faster and to minimize outward leakage of humid air.

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Stand Density, Soil Climate, and Litter Decomposition

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Studies are done on soil climate and litter decomposition in different stands of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) at several locations in Northern Europe and Scandinavia. Special interest is given to how the stand density governs soil climate. A physically based coupled heat and water model (Jansson and Halldin 1979) was used as a tool to analyze soil climate processes. Soil temperature, soil moisture, and snow depth were intensively measured at one location in Sweden to test the model. In spite of the differences in energy balance at the soil surface in open and closed stands, similar soil temperatures in shallow soil layers were observed during some periods. At deeper depths a more rapid increase in temperature was observed in the open stand compared with the closed stand. The similar temperatures at shallow depths were explained by differences in ground vegetation and by the low heat conductivity of the surface layers in the dense stand. Below the dense stand no vegetation was found, only a carpet of litter covered the ground. The measurements can then be used to estimate the parameters in the soil climate model. Soil climate simulations can then be done with standard meteorological data for other sites. The results from the soil climate simulations can hence be used, for instance, as input to a litter decomposition model (Jansson and Berg 1985) establishing a possibility to analyze decomposition rate according to the local soil climate.

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The following poster presentations are unavailable:

Direct Reading X-Ray Densitometer
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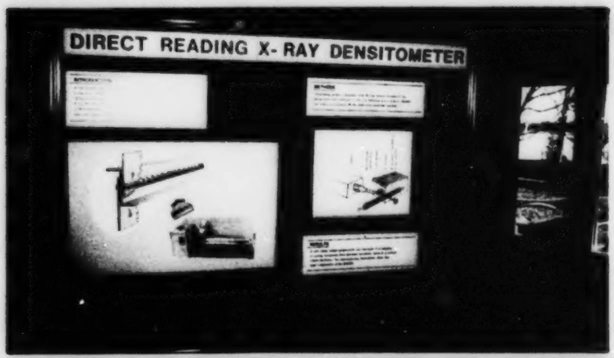
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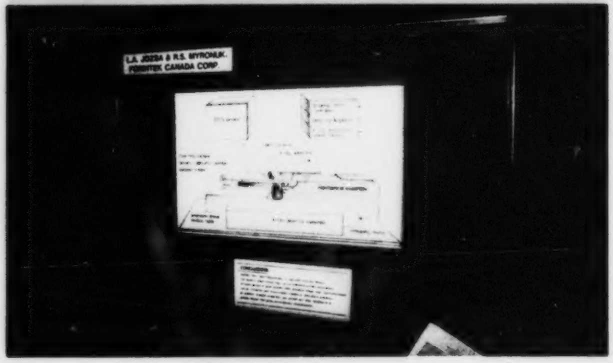
L.A. JOZSA & R.S. MYRONUK.
FORINTEK CANADA CORP

Operational Software for Integrated Simulation of Weather and Soil Influences on Nursery Crops
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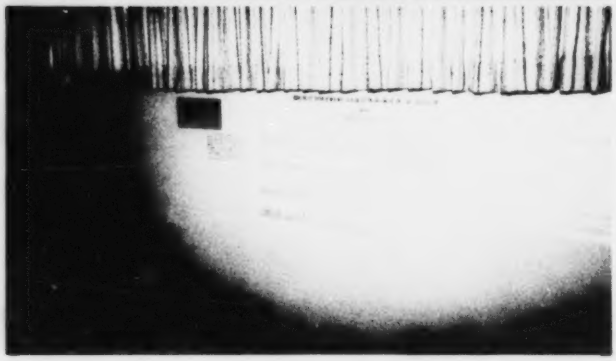

Modeling Soil Water Availability for Seedling Establishment
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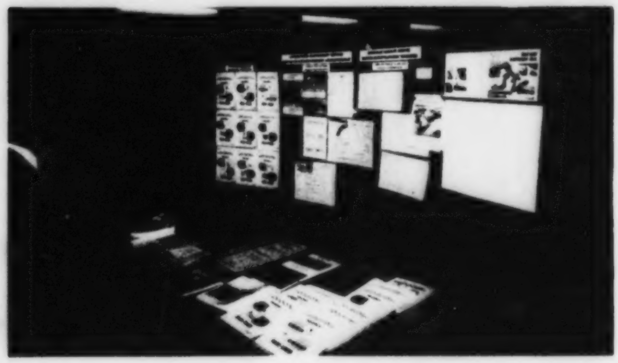

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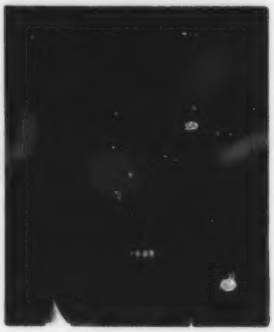

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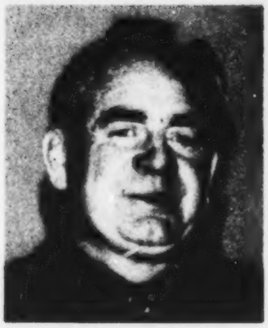

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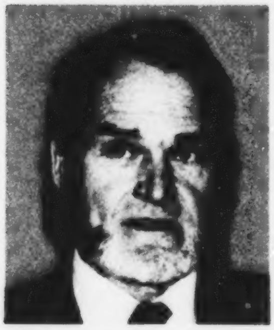

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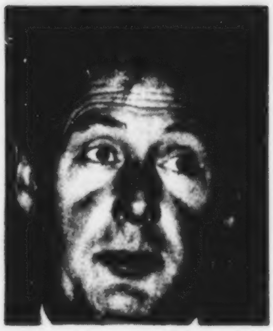

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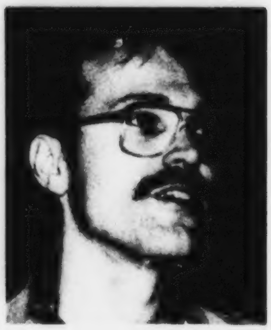

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Appendix: Summary of Recommendations

SESSION I. Climatic Applications in Seed and Stock Production

1. Education and training courses in climate and its measurement be established to transfer climate knowledge into the seed/stock production sector of forestry;
2. Process studies and computer software models be developed to integrate current weather and climate knowledge into day-to-day operations (e.g., climate-based irrigation scheduling and synoptic forecasting for nursery practices);
3. Upgrading of all nursery locations with computerized climate datalogging systems and the development of the software to assist current forestry operations. This software will include appropriate computerized models (e.g., for nursery and seed orchard management);
4. Genetic breeding zones be integrated with climate productivity zones for forest renewal management (microscale to macroscale climate integration);
5. Interagency team cooperation be encouraged to increase the delivery, effectiveness, and implementation of current climatic knowledge into forestry renewal.

SESSION II. Climatic Applications in Forest Regeneration

1. Methods for integrating climate information at the macro- and mesoscales into the preparation of silviculture prescriptions be developed and transferred as an operational planning tool for foresters;
2. Climate information be integrated as a primary factor into forest site classification field manuals including the necessary information to interpret mesoscale climates from available data (e.g., macroscale climate and topographical data) to develop site-specific prescriptions; and
3. Models that define the framework for silviculture prescriptions be developed and transferred to operational foresters. This will require biologically sensitive forestry data such as that provided by the growth layer reconstruction technology (e.g., TRIM system, Ontario Ministry of Natural Resources).

SESSION III. Climatic Applications in Forest Growth and Development

Forest Production

1. Relationships between climate and methods of forest productivity acceleration or optimization be given greater emphasis in studies and in particular that the results be capable of being related from small- through large-scale climatologies;
2. Stand modification for microclimate alteration be examined for its impact on productivity; and
3. Associations between climate and treatment effectiveness be examined for better definition of application windows (e.g., fertilization, spraying).

Forest Depletions

Fire

1. The need for updating and improving fire weather station networks (i.e., siting and instrumentation) be examined and that the possibility of multipurpose (i.e., fire and silviculture) weather stations be explored. This process can be relatively simple and inexpensive considering the increasing availability of reasonably priced automated dataloggers:
2. Methods be developed to integrate weather information from various sources (e.g., satellite, radar, and lightning locator systems) into the forest fire intelligence system to achieve a better assessment of spatial variability in airmass or weather component of the fire environment; and
3. Research be accelerated into assessment of the impact of synoptic-scale climate and weather on the occurrence and behavior of forest fires and that the results of this research be transferred to the operational level.

Insects

1. Training of involved staff be undertaken to integrate known technological procedures into operational spray programs including the definition of the effective spray window in terms of physiological and weather data relationships including the selection, setting-up, and use of appropriate meteorological observation systems;
2. The current understanding of the relationships between insect population dynamics and climate be expanded through appropriate studies to include all the significant forest insect species and, where the parasites play an integral role in the pest population dynamics, the relationship between climate and parasite populations;
3. The relationship between weather/climate and spray program effectiveness be defined objectively and the technology transferred to the operational level.

Pollution

1. An integrated effort (climate, soil, and tree physiology) be undertaken to develop a comprehensive simulation of forest productivity using detailed growth layer data; and
2. Climate stresses (including airborne pollution) be identified, evaluated, and documented and that this information be recorded annually as forest depletions (or accelerations) in forest management planning and allowable cut models.

Climate Change

1. The impact of CO_2 on forest systems be examined in the forest environment including the implications regarding water efficiency, biological productivity, and the relationships between crops and weeds;
2. An integrated (climate and physiology) forest productivity model be developed in which climate is the driving factor and various climate scenarios (change and variability) can be examined leading to sensitivity analyses related to productivity;
3. Forest systems and regions most susceptible to change when climate is altered be identified. This will supply forest managers, for example, with information directly applicable for species and site selection alternatives and current timber resources.
4. Models capable of examining the implications of climate change and variability on forest pests, diseases, and fire be developed.

SESSION IV. Climatic Applications in Forest Utilization and Economics

Climate and Wood Quality

1. Forest growth and wood quality studies be combined with climatic technology to enhance wood supply management;
2. Site-specific process studies that identify both the growth and wood density changes over time and their variability in space be encouraged. This is particularly important for selecting and planning the characteristics of the new forest; and
3. Computerized hardware and software development be accelerated to increase the application of wood density analysis into operational forest practices.

Harvesting/Transportation/Utilization

1. Synoptic forecasting and climatologies, risk analyses, and site-specific climate prescriptions be incorporated into harvesting and transportation activities to optimize oeprations; and
2. Increased monitoring of specific utilization characteristics of the wood supply be encouraged in light of the industrial requirements for known wood properties.

Economic Value of Climate

1. Silviculture investments and timber production economics models be expanded to include the integration of climate for the optimization of forest-management solutions (the appropriate climatic data bases are currently available at the macro- and mesoplanning levels; and
2. The forest climatology commmunity identify and cost-justify the impact of climate in operational management activities (this will involve the development of new methodologies).